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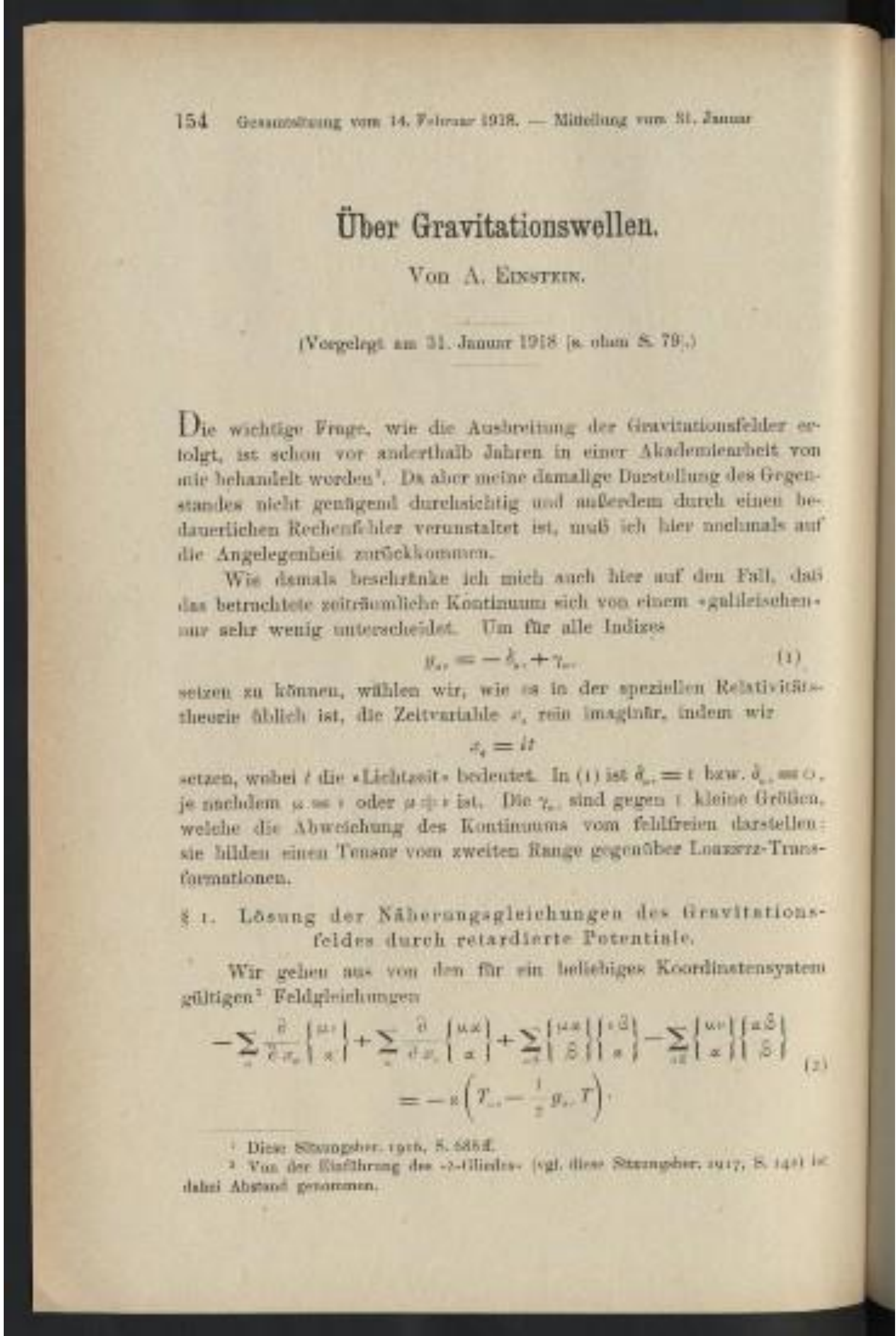
19 September 2023

Kilonovae: the cosmic foundries of heavy elements (Part I)

Elena Pian
INAF-OAS, Bologna

Gravitational waves are "ripples" of Spacetime, produced by accelerated masses and predicted by General Relativity theory (Einstein 1916, 1918)



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\kappa\left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right). \tag{2}$$

---

[1] Diese Sitzungsber. 1916, S. 688ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

AMPLITUDE AND POWER OF A GRAVITATIONAL WAVE

If *R, M, v* are the characteristic size, mass, and speed of the emitting source, and *r* is our distance from the source, we have:

Amplitude:

$$h \sim \frac{r_{\mathrm{Sch}}}{r} \frac{v^2}{c^2},$$

Where *r_Sch* is the Schwarzschild radius of the emitting source: *r_Sch = GM/c^2*

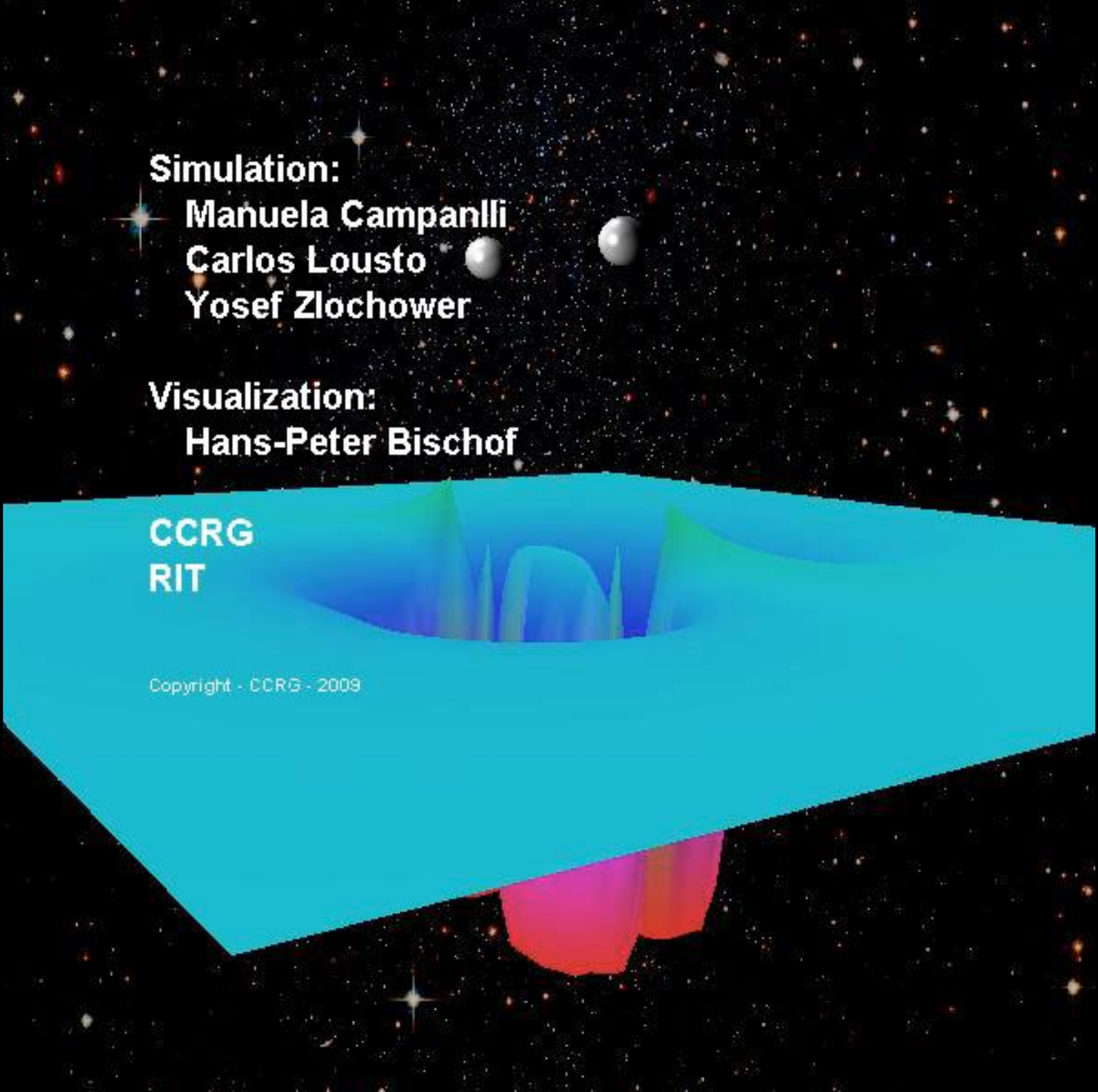
Luminosity:

$$\frac{dE}{dt} \sim \frac{G}{c^5} \left(\frac{M}{R} \right)^2 v^6 \sim L_0 \left(\frac{r_{\mathrm{Sch}}}{R} \right)^2 \left(\frac{v}{c} \right)^6,$$

where

$$L_0 \equiv \frac{c^5}{G} = 3.6 \times 10^{59} \text{ erg s}^{-1}.$$

S.Shapiro & S.Teukolsky 1983, *Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects*



Simulation:

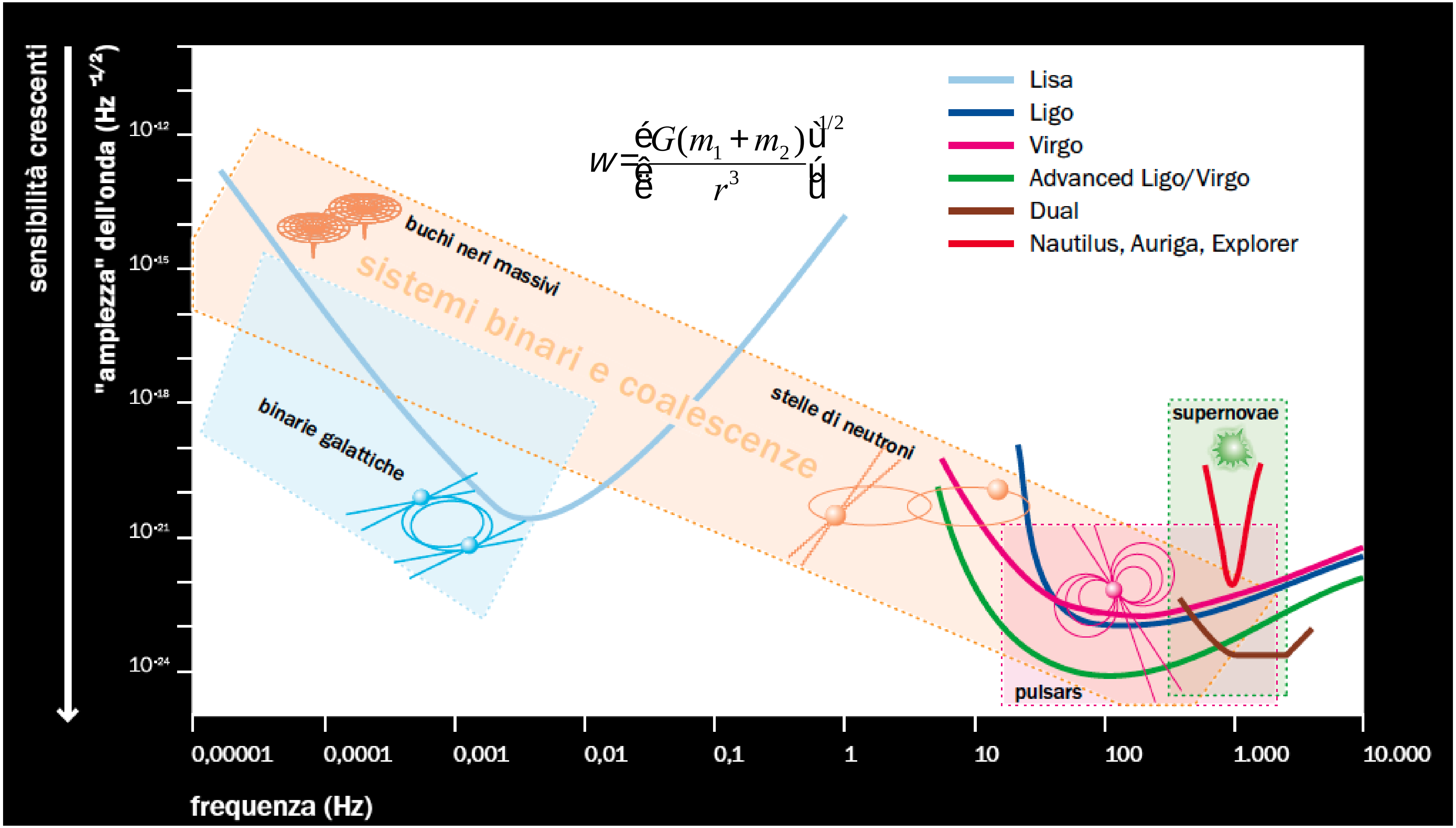
Manuela Campanlli
Carlos Lousto
Yosef Zlochower

Visualization:

Hans-Peter Bischof

CCRG
RIT

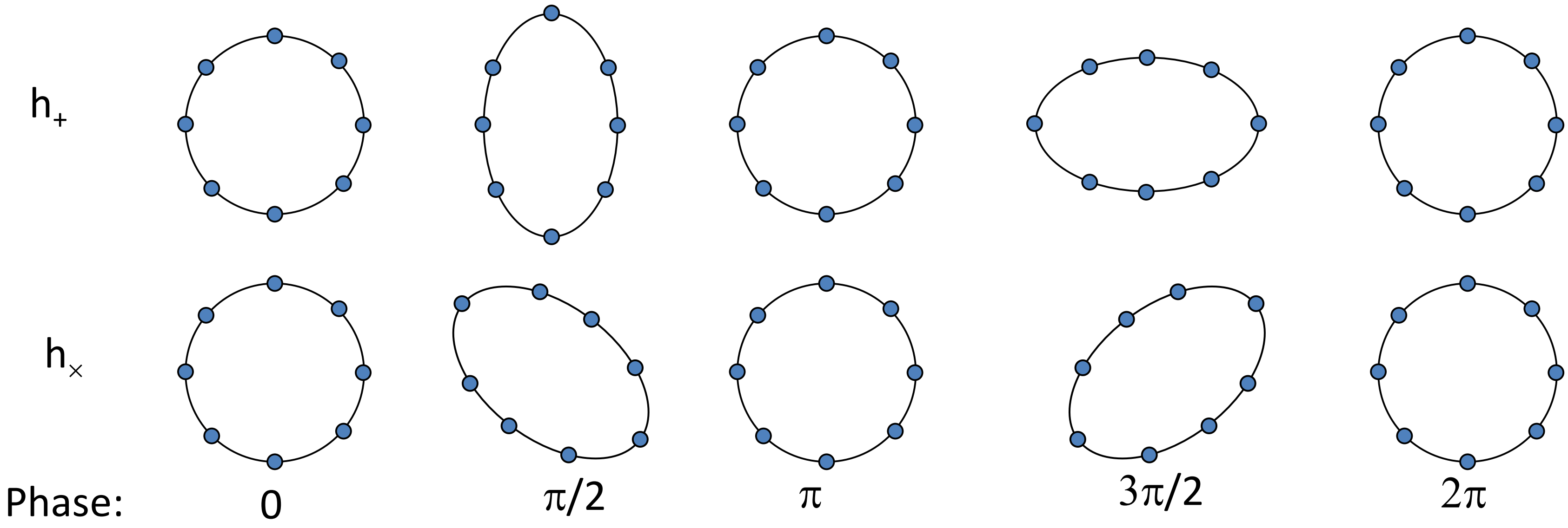
GW amplitude-frequency diagram of known cosmic sources

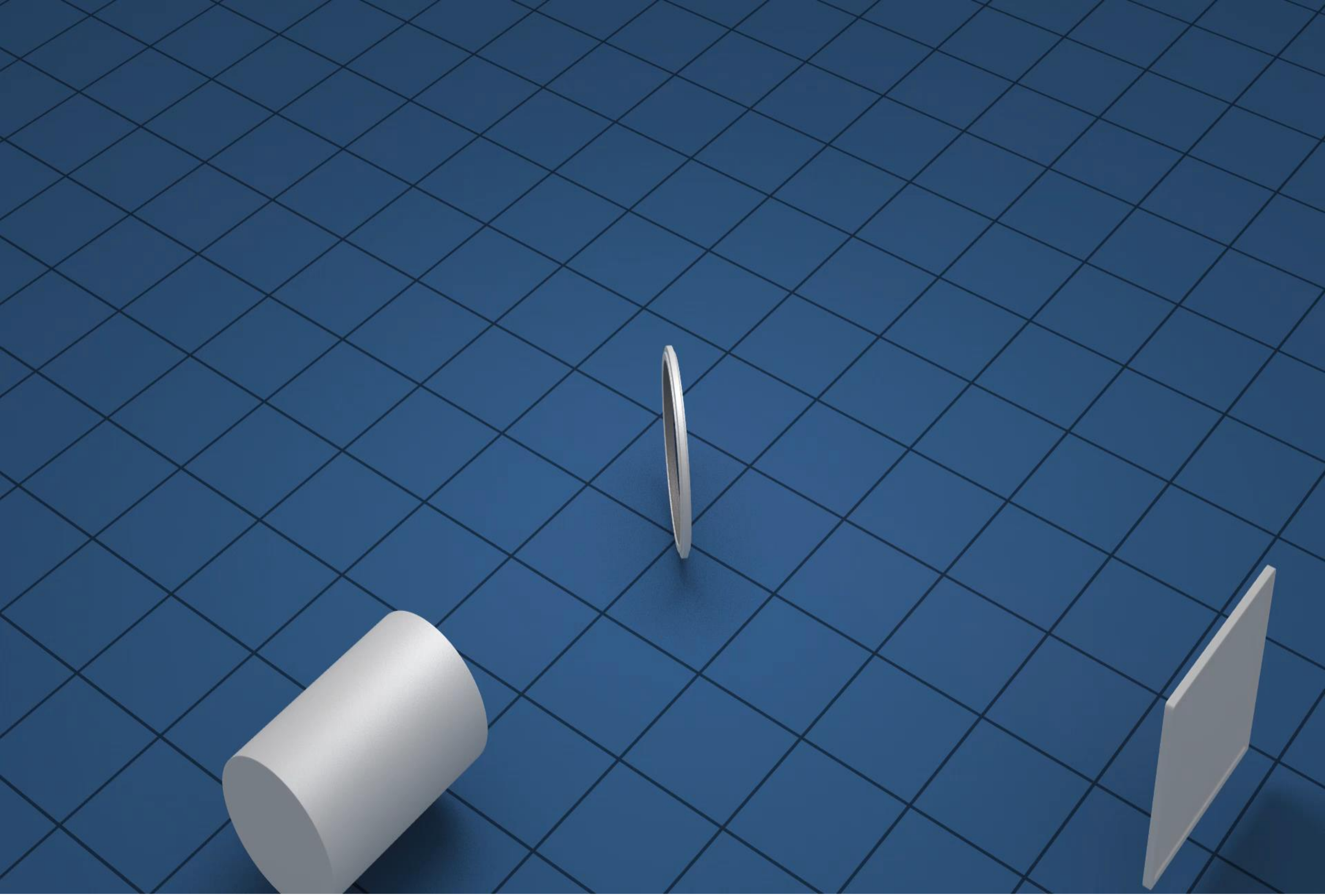


$$w = \left[\frac{G(m_1+m_2)}{r^3}\right]^{1/2}$$

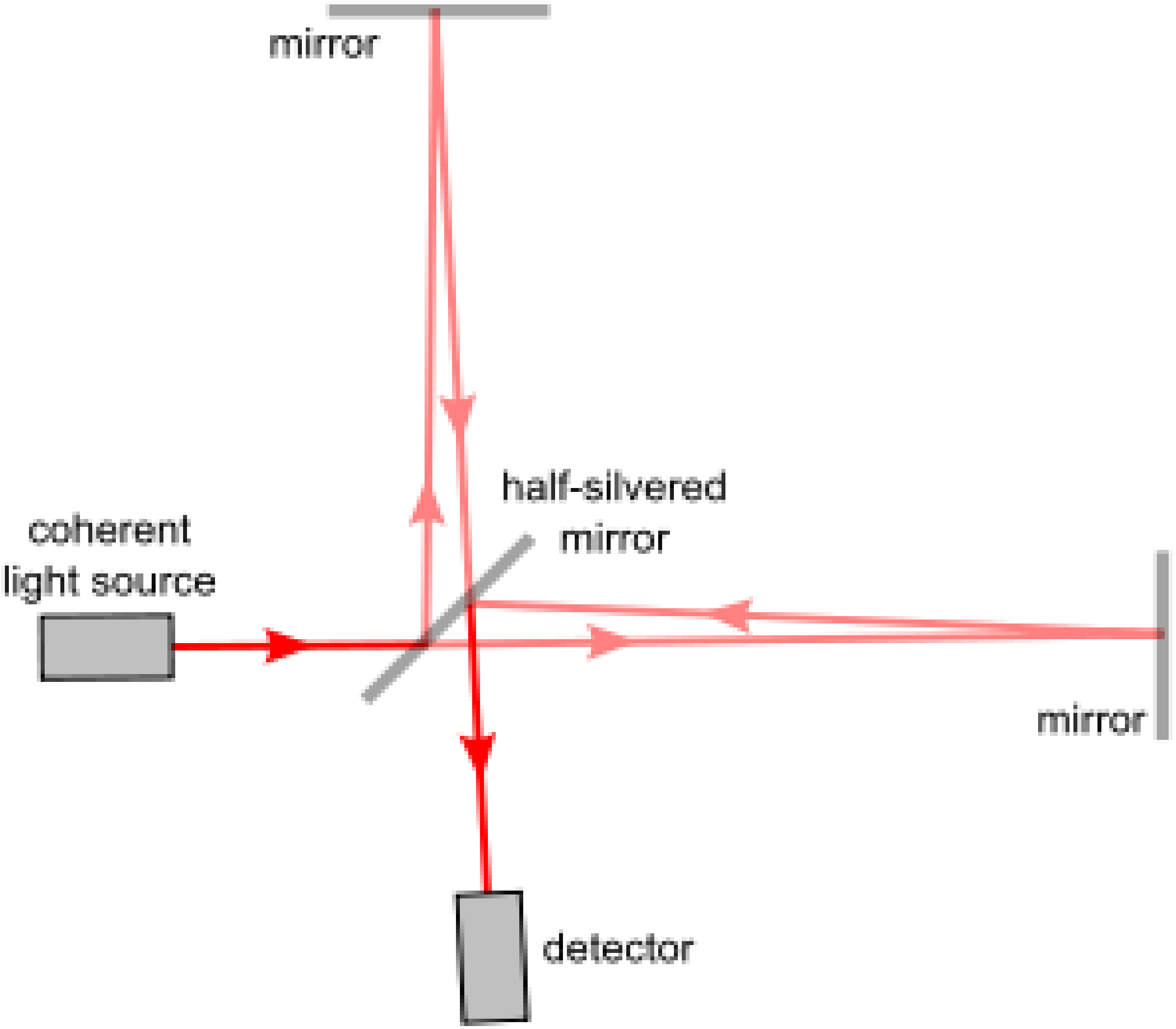
Polarization of GWs

GWs have 2 different linear polarizations. The 2 states are rotated 45 deg relative to one another. This contrasts with the 2 polarization states of an electromagnetic wave, which are 90 deg to each other. This pattern of polarization is due to the fact that gravity is represented by a second-rank symmetric **tensor** ($h_{\mu\nu}$), while electromagnetism is represented by the **vector** potential A^{mu}





Scheme of a laser interferometer

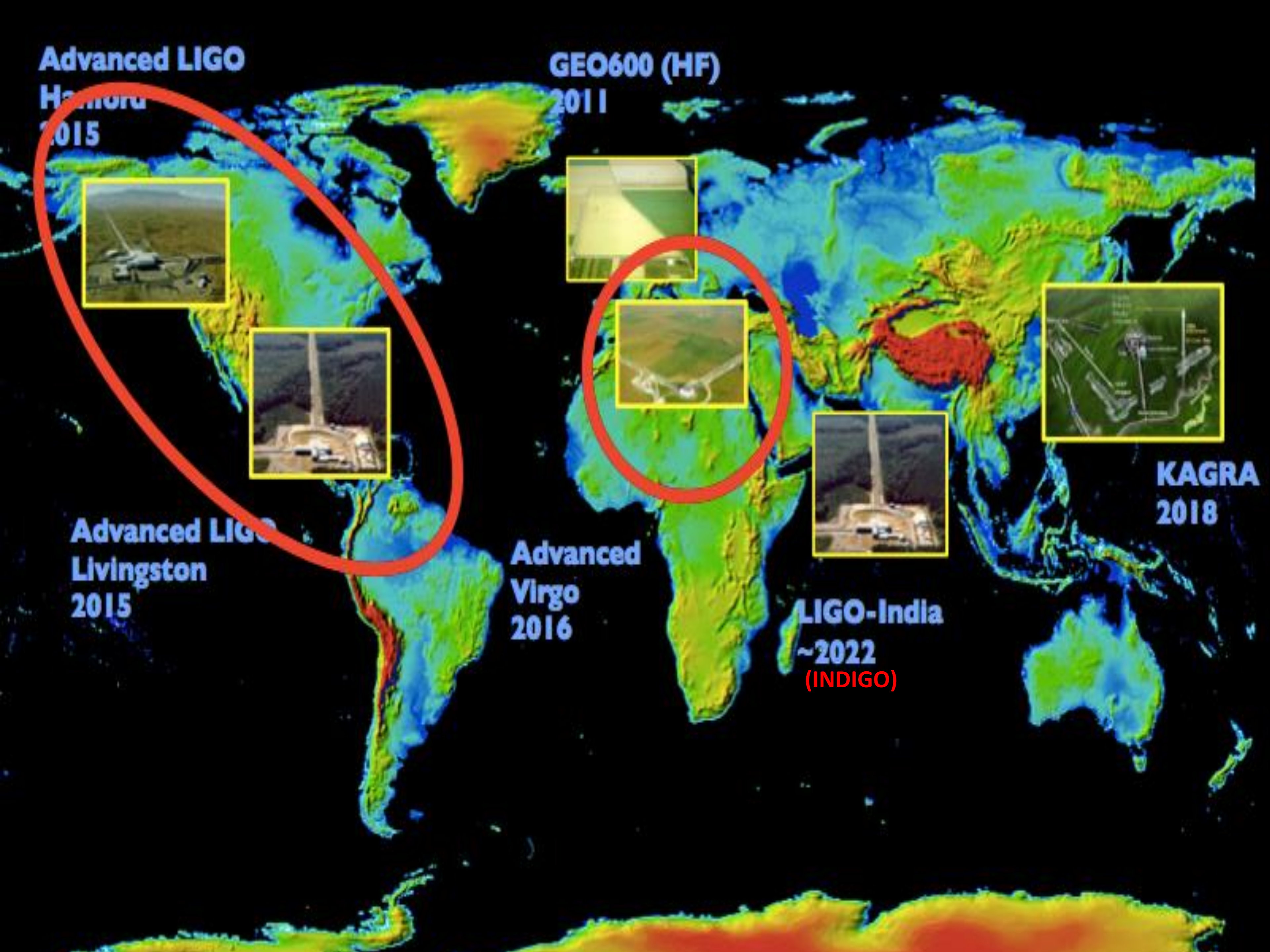


$$h = \frac{\Delta L}{L}$$

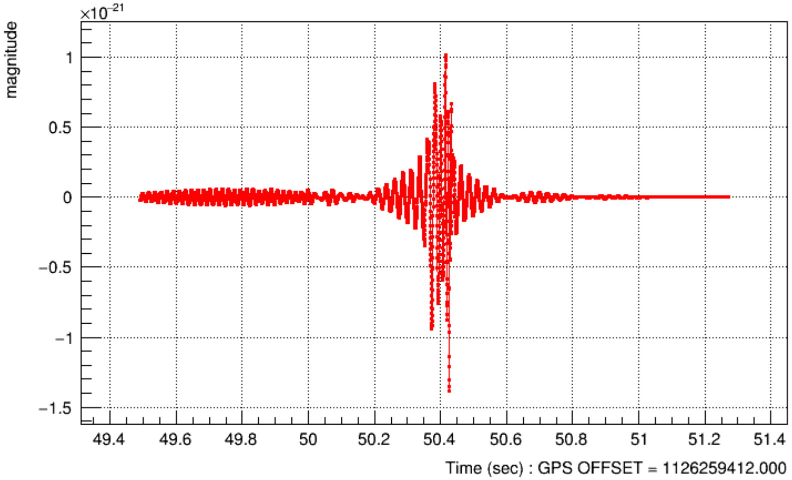
Fourth Observing Run (O4):
<u>May 2023</u>

GRAVITATIONAL INTERFERO-METER NETWORK: LIGO, VIRGO, KAGRA

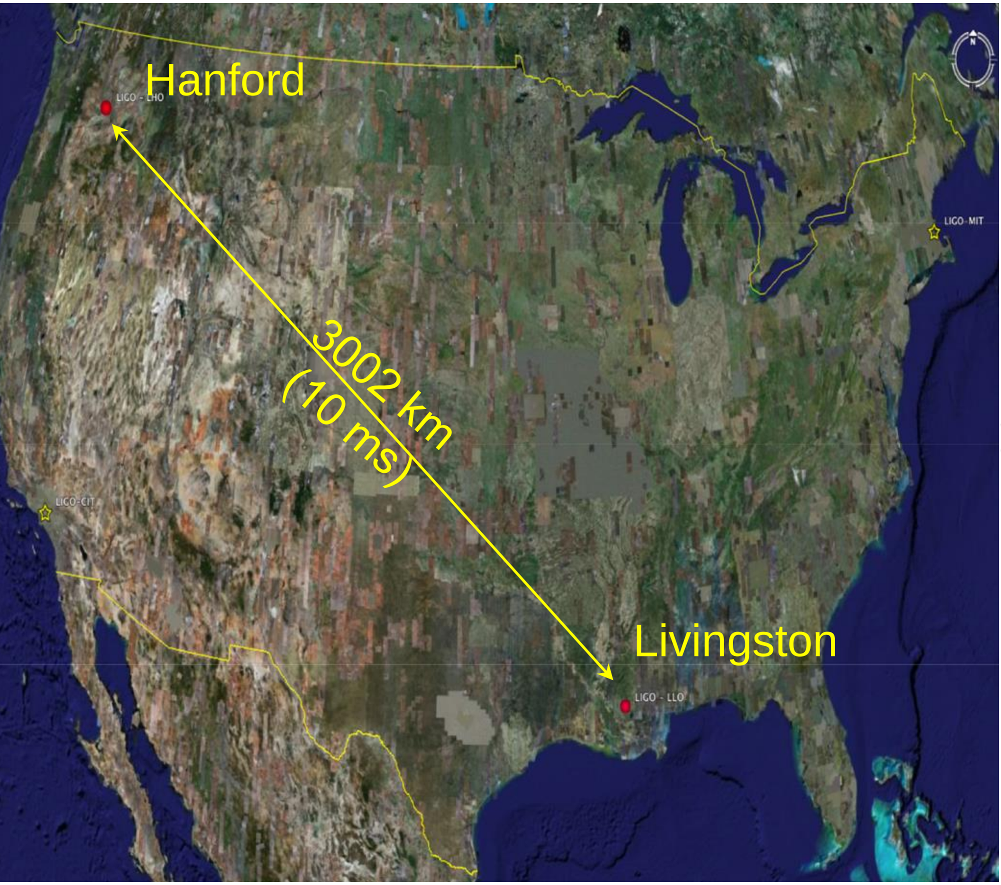
Credit: LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration


Advanced LIGO Hanford 2015
GEO600 (HF) 2011
Advanced LIGO Livingston 2015
Advanced Virgo 2016
LIGO-India ~2022
KAGRA 2018

(INDIGO)

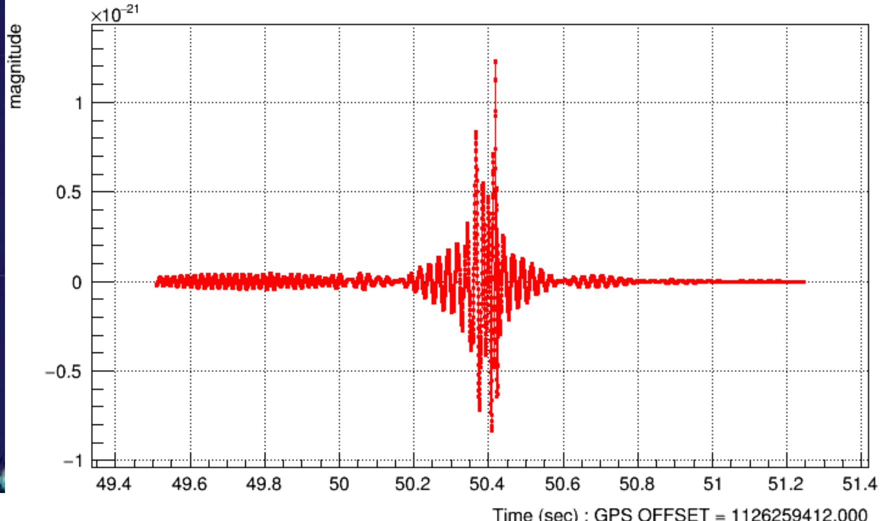


September 14, 2015 at 11:50:45 in Central European Time

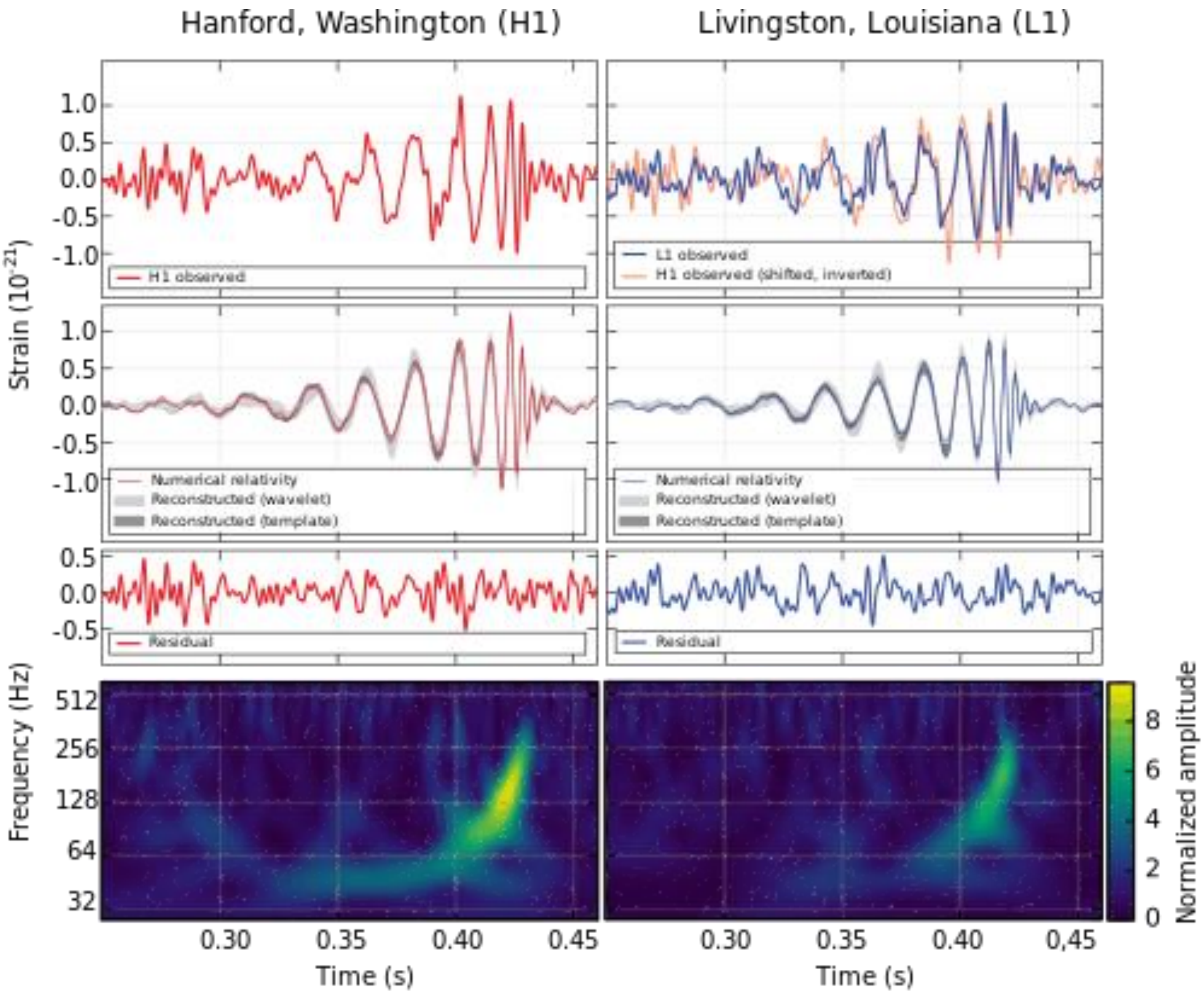


Alarm reported by the on-line algorithm for generic transient search

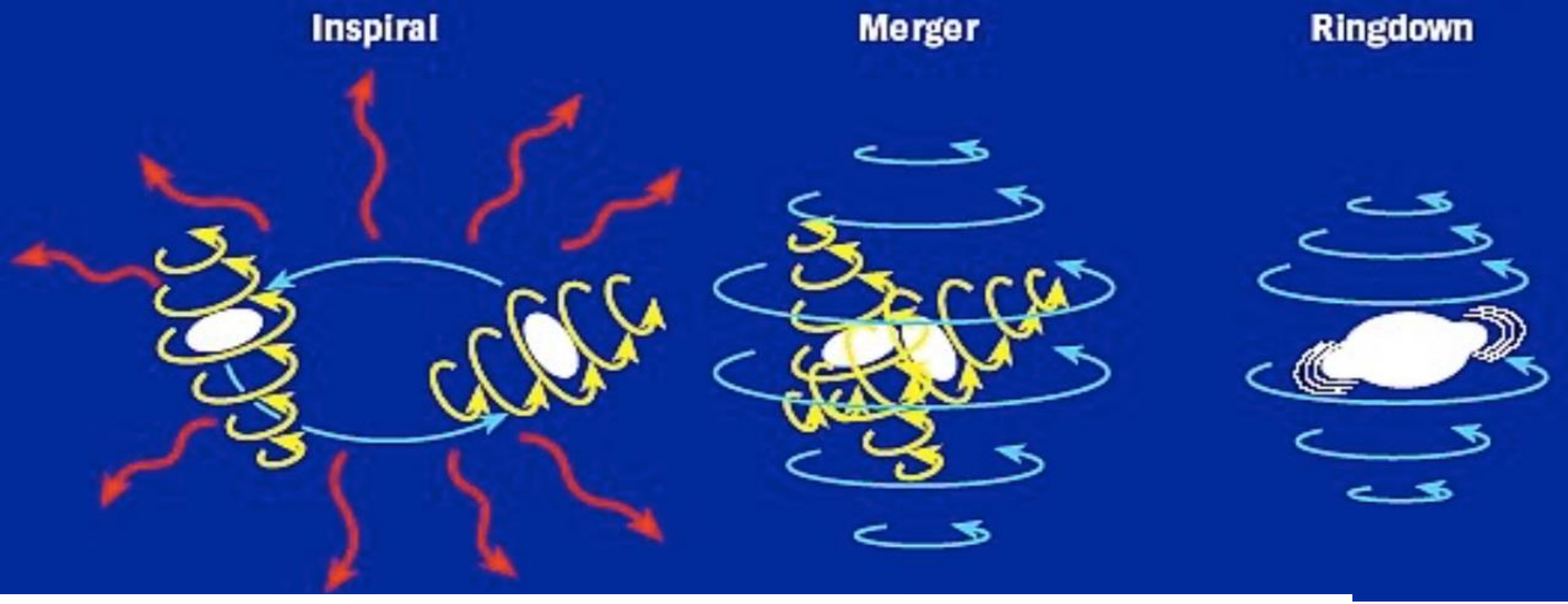
SNR =24

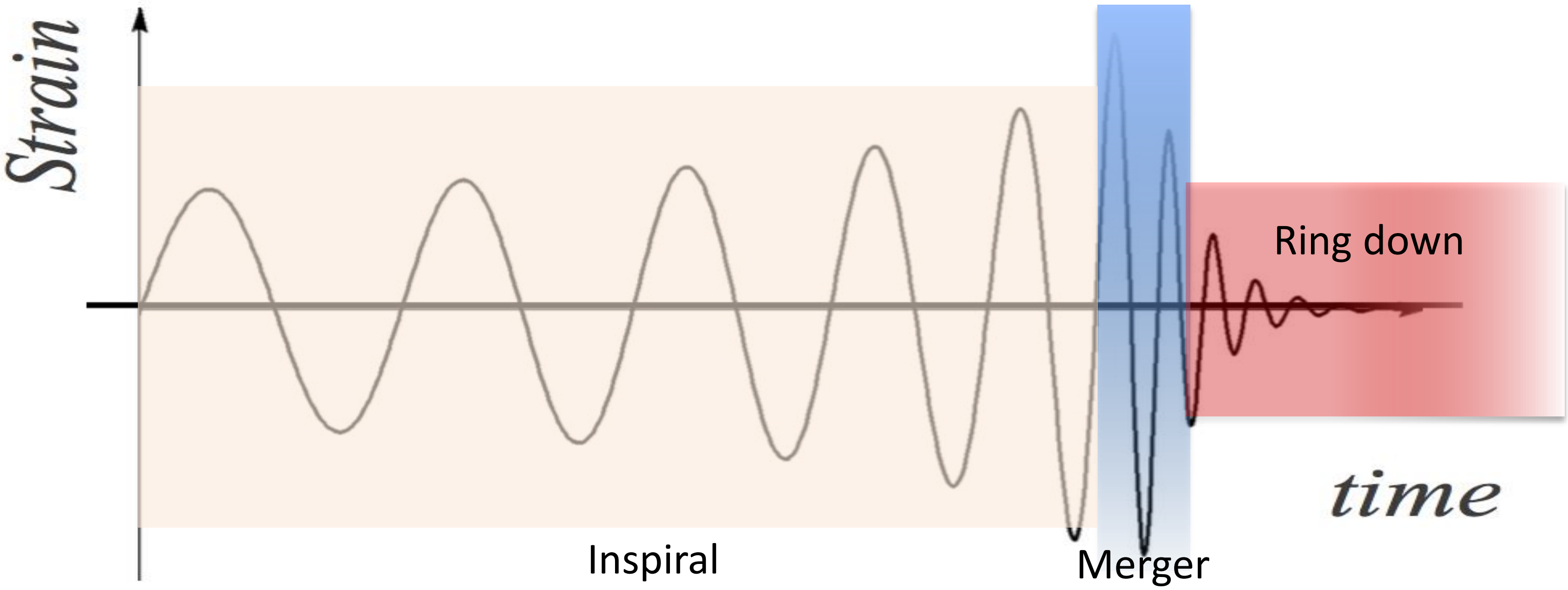


14 September 2015: First detection of gravitational waves



Abbott et al. 2016


Inspiral
Merger
Ringdown

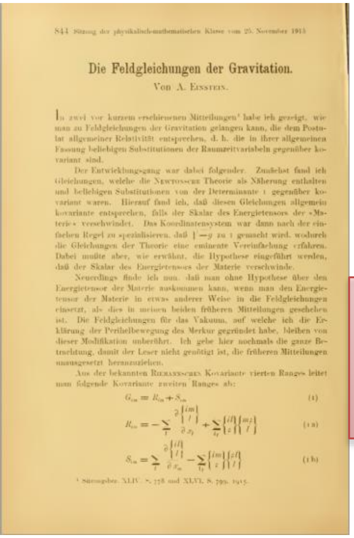

Strain
Ring down
time
Inspiral
Merger

Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016)
PHYSICAL REVIEW LETTERS
week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)


844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

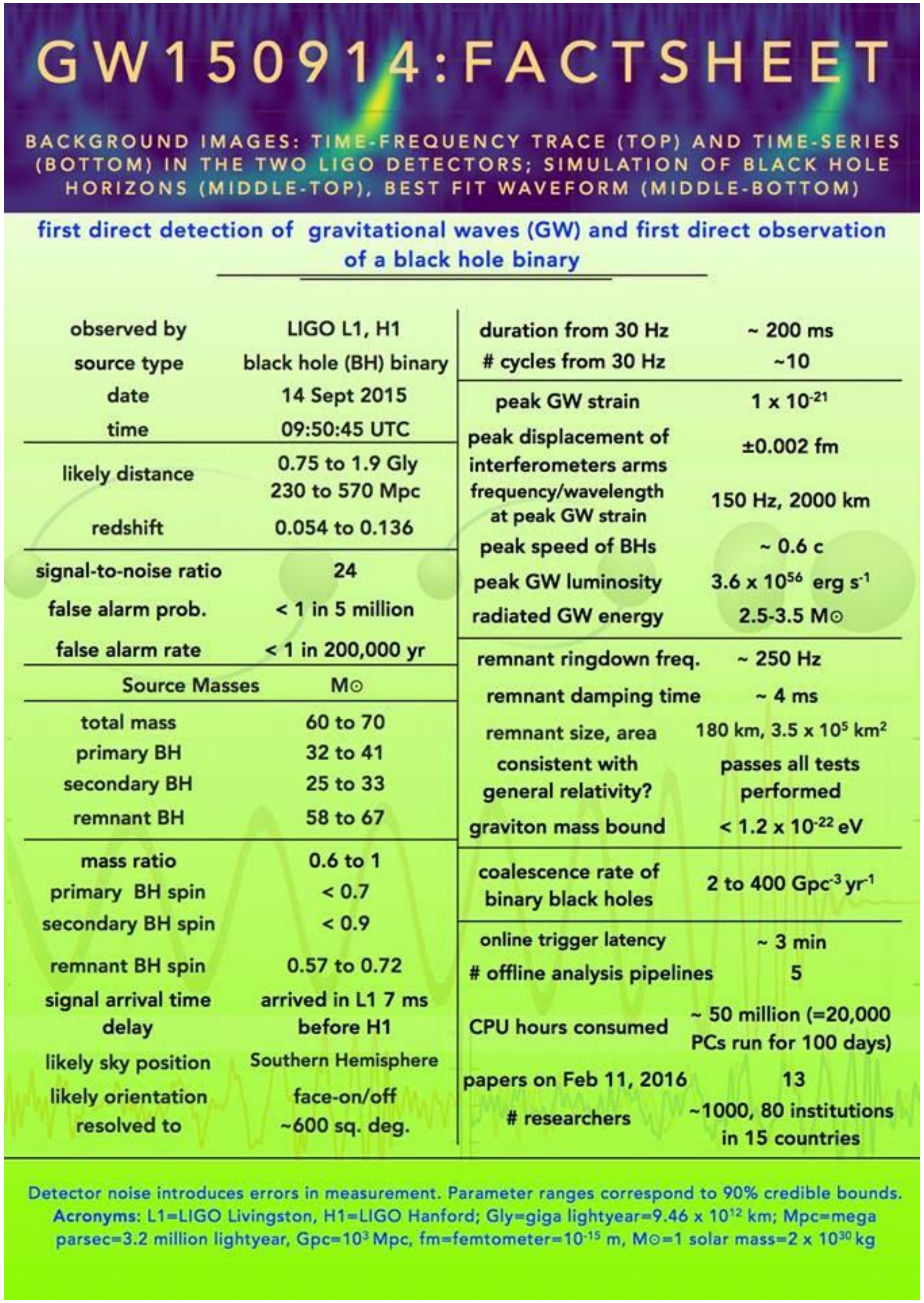
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.


Über Gravitationswellen.

Von A. Einstein.

DOI: 10.1103/PhysRevLett.116.061102

http://link.aps.org/doi/10.1103/PhysRevLett.116.061102



GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

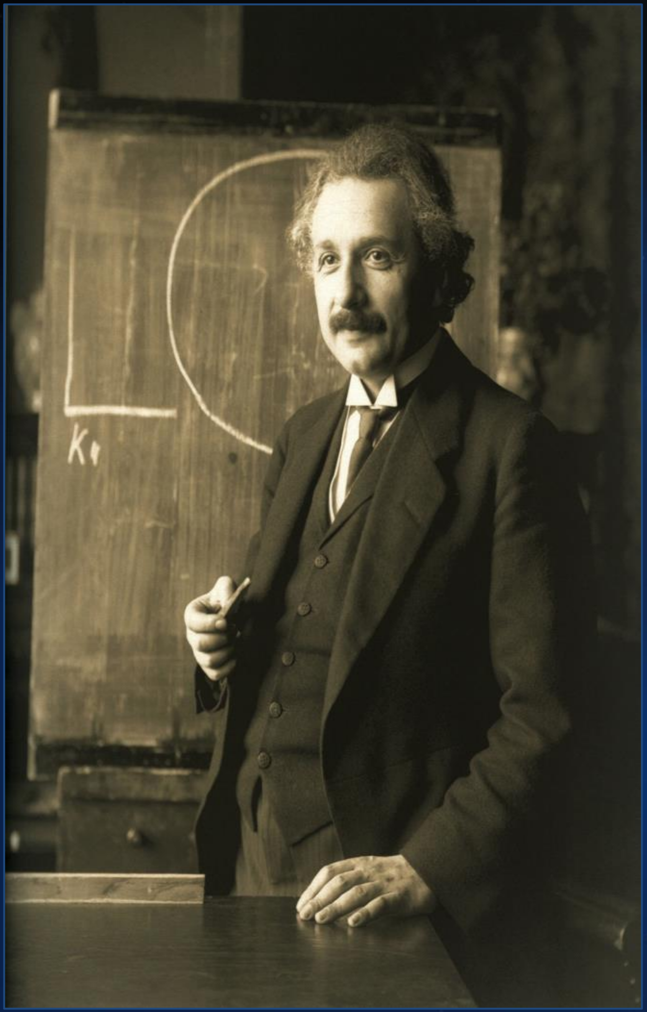
first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

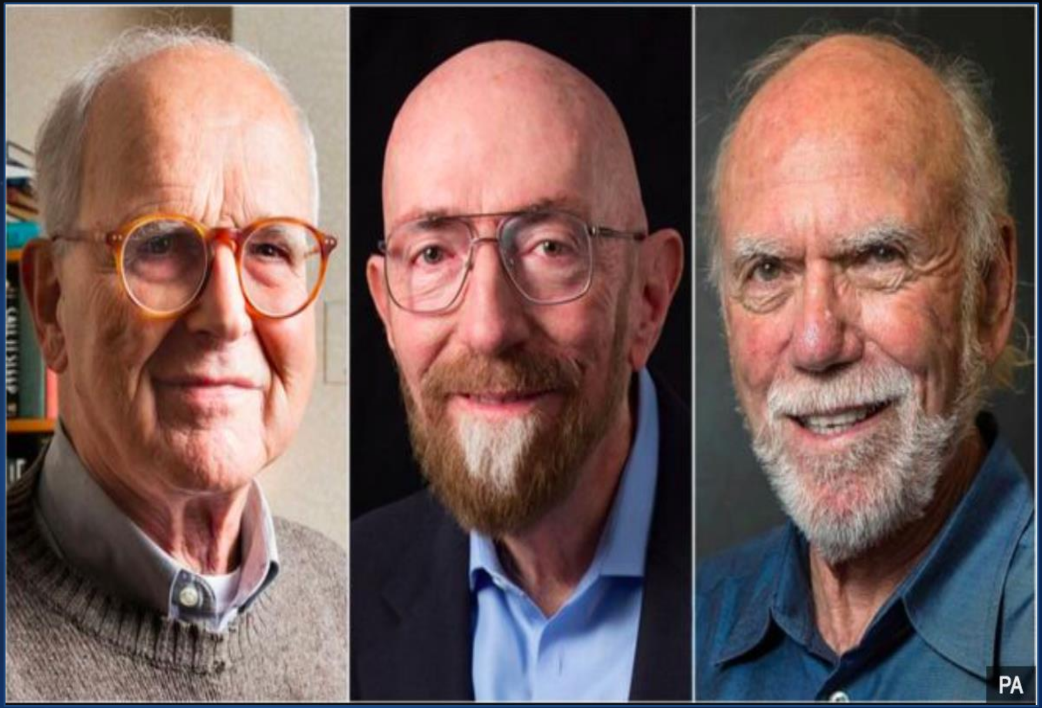
duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds. **Acronyms:** L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

Gravitational Waves

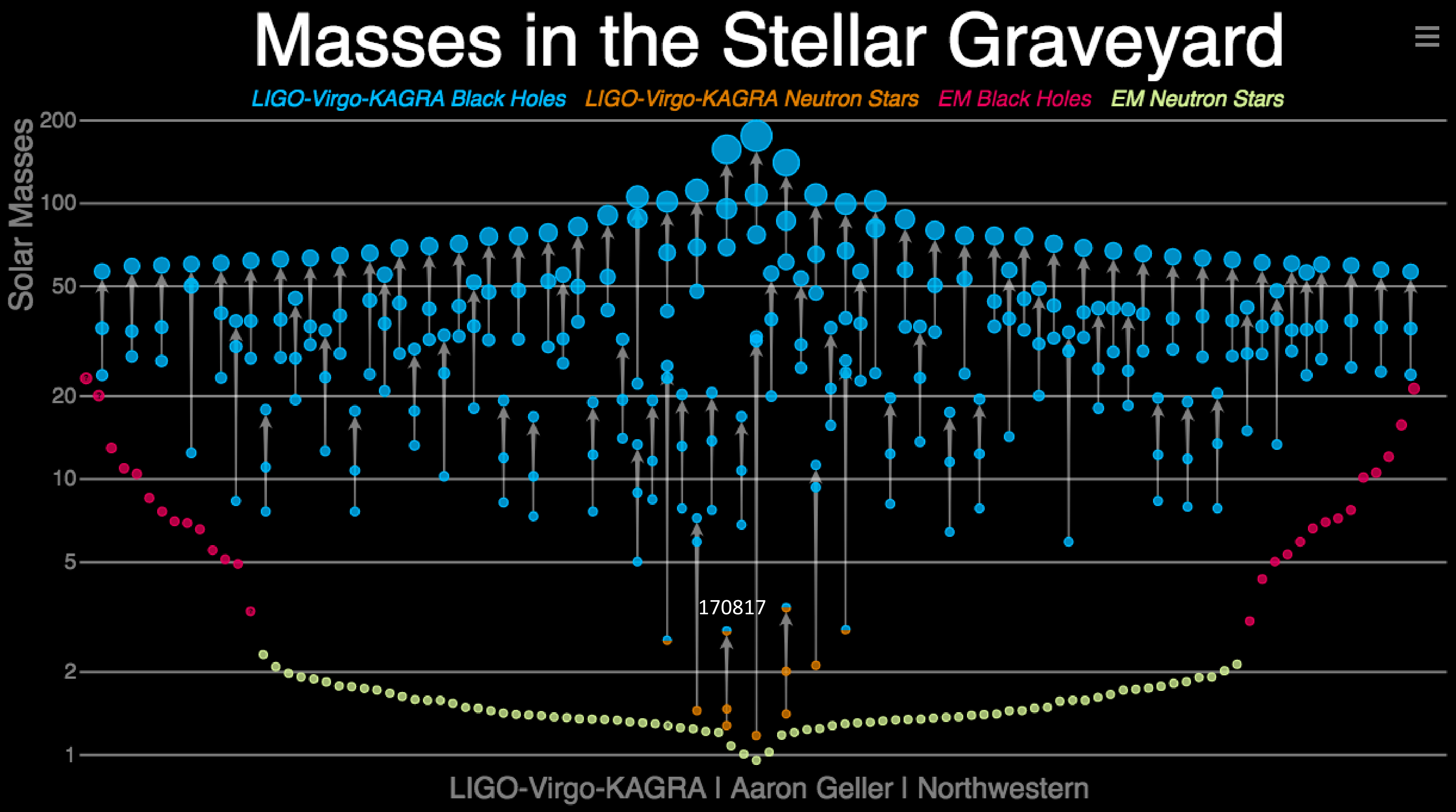


A. Einstein 1916



R. Weiss K. Thorne B. Barish

Nobel Prize for Physics 2017



Masses in the Stellar Graveyard

https://ligo.northwestern.edu/media/mass-plot/index.html

While black hole mergers are expected to be electromagnetically "silent", neutron star mergers (or mergers of a NS and a BH) are expected to be accompanied by an electromagnetic signal.
The mergers of systems containing at least a NS present thus a large potential for:

1) determining the NS equation of state

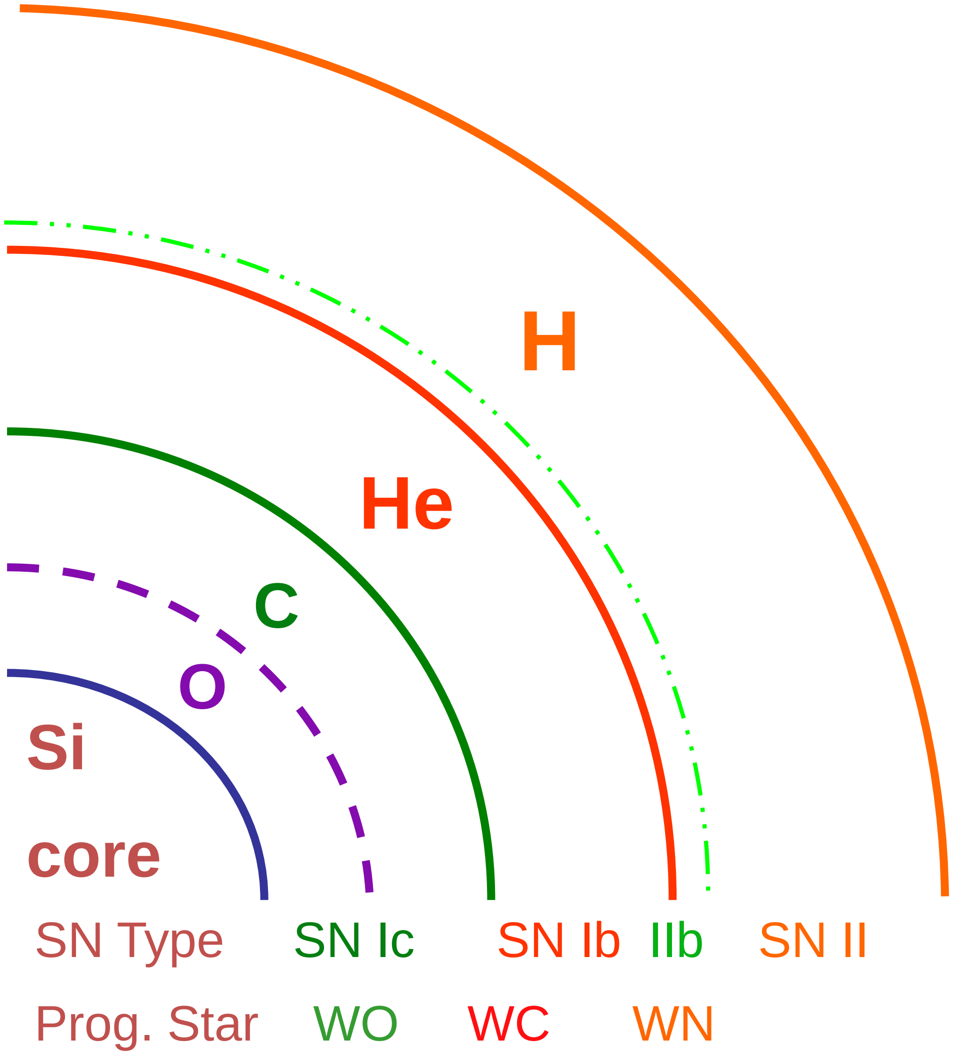
2) mapping the history of heavy elements formation

3) Studying the progenitor population of short GRBs

Mass of star determines its fate

Mass of Progenitor star	Remnant
$<3M_\odot$	He White Dwarf
$3\text{-}6\ M_\odot$	C-O White Dwarf
$6\text{-}8\ M_\odot$	O-Ne-Mg White Dwarf
$8\text{-}23\ M_\odot$	Neutron Star
$23\text{-}{\sim}140\ M_\odot$	Black Hole
$>{\sim}140\ M_\odot$	None?

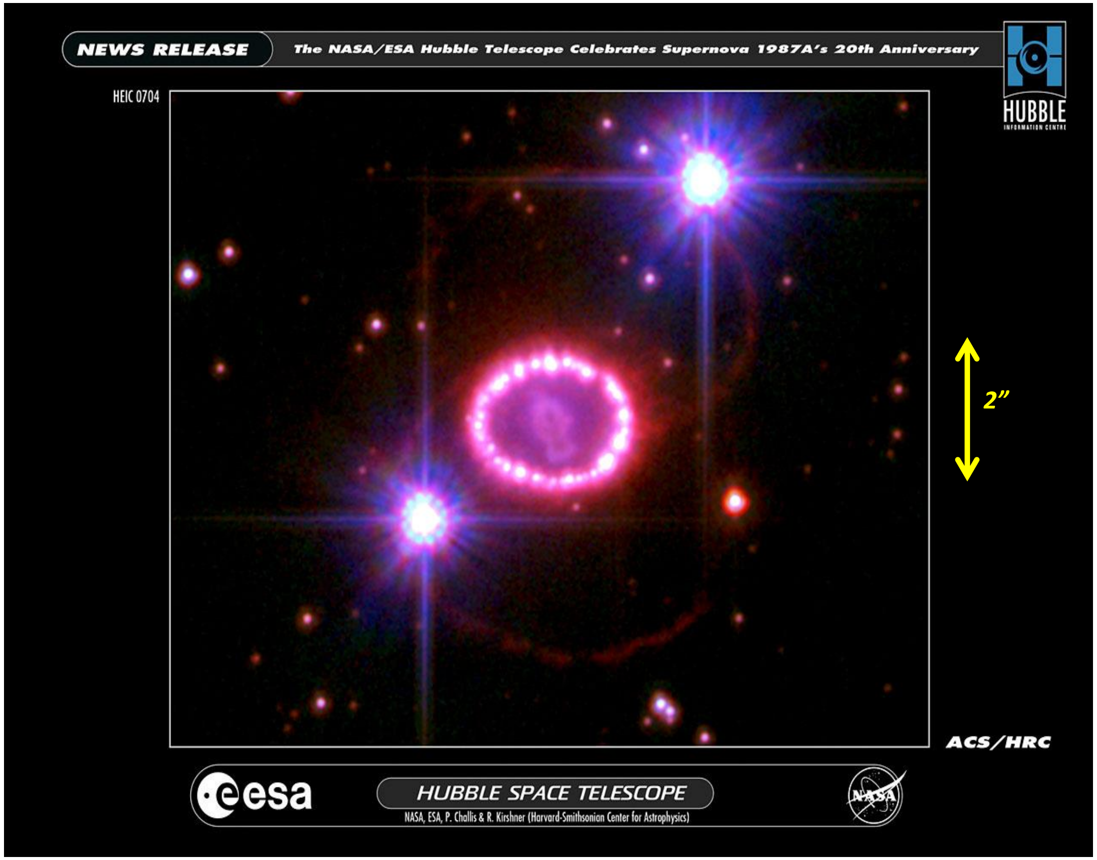
Massive Stars ($>8M_{\odot}$)



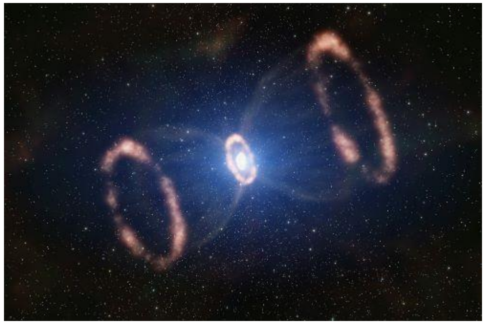
- Si burning → Fe core
- Core collapse
- Compact object (NS/BH)
- ν emission
- KE deposited (~10^{51}erg)
- Nucleosynthesis
  → ^{56}Ni (~$0.1M_{\odot}$)
- envelope ejection
- SN type depends on degree of stripping
  - Role of binarity?

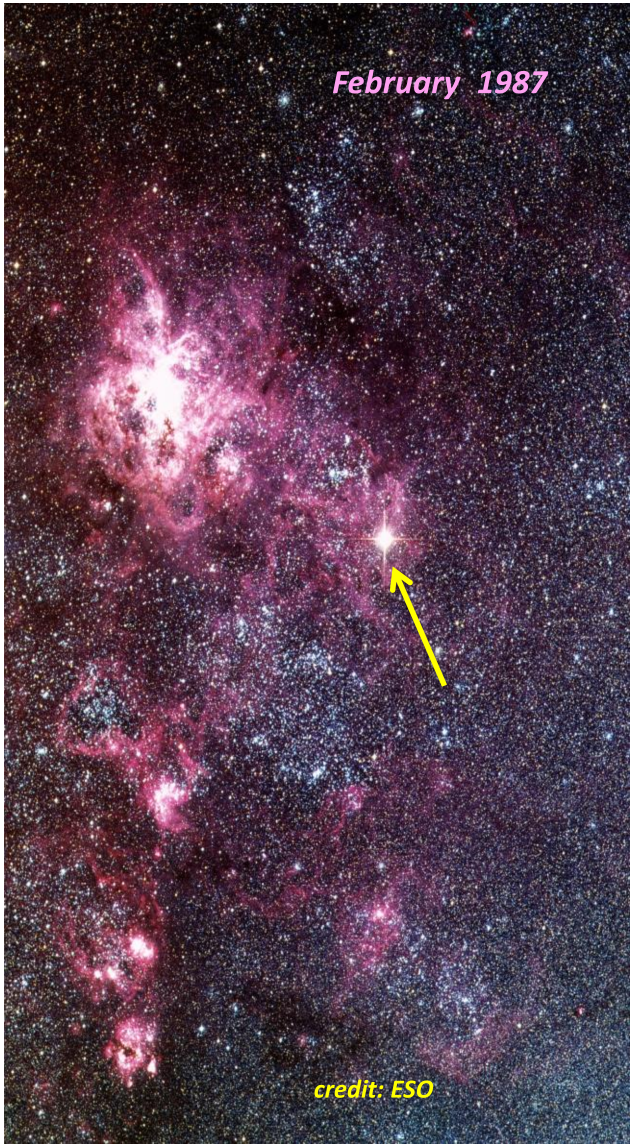
SN1987A: core-collapse supernova in the LMC (50 kpc)

First example of multi-messenger astronomy (barring the Sun…)!!!



artist concept of SN1987A



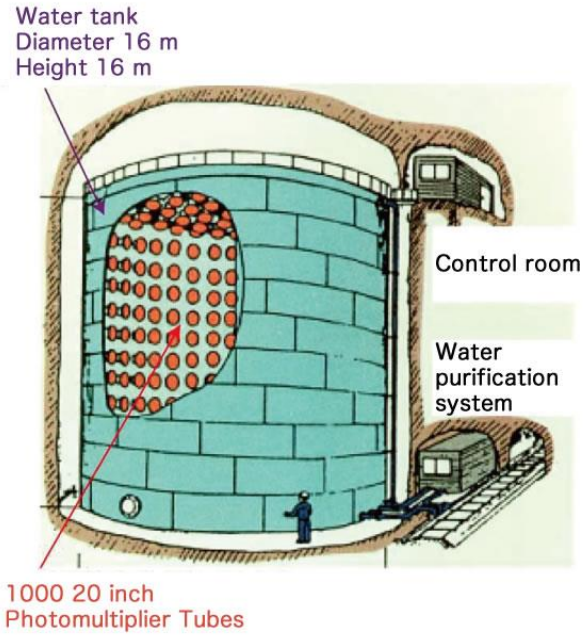


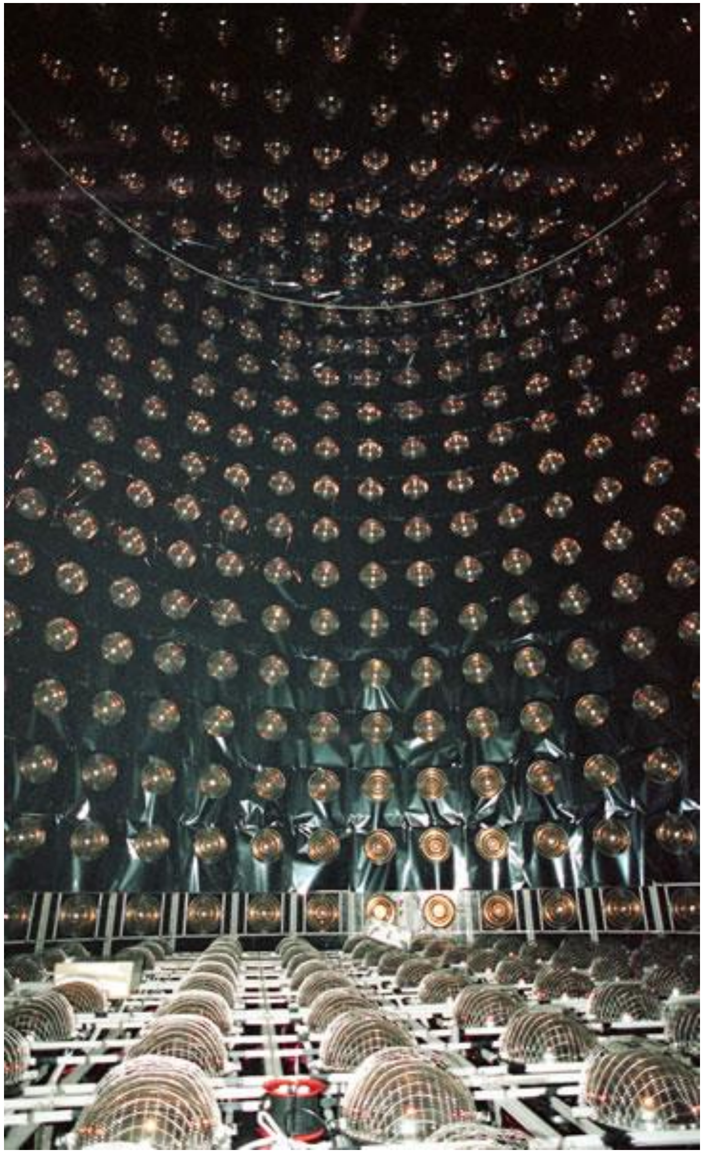
February 1987

credit: ESO

SN1987A: MeV neutrino detection Proves core-collapse and neutron star formation

The neutrino detectors IMB (USA), Kamiokande (Japan) and Baksan (Russia) detected a handful of neutrinos each, a few hours before light detection from SN1987A (I. Shelton 1987, IAU Circ. 4316)





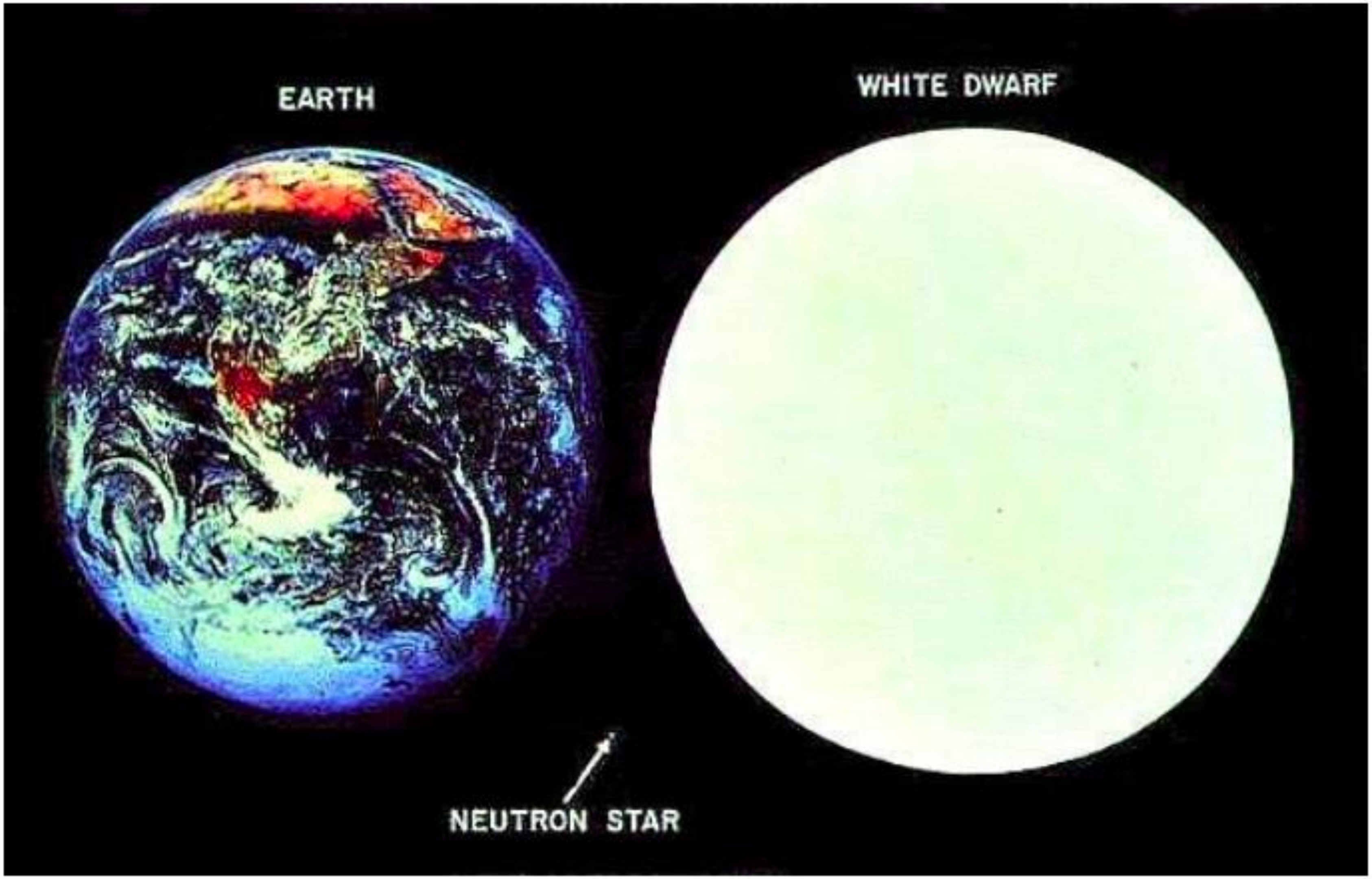
Core-collapse supernova neutrinos

Electron capture (or inverse beta decay):

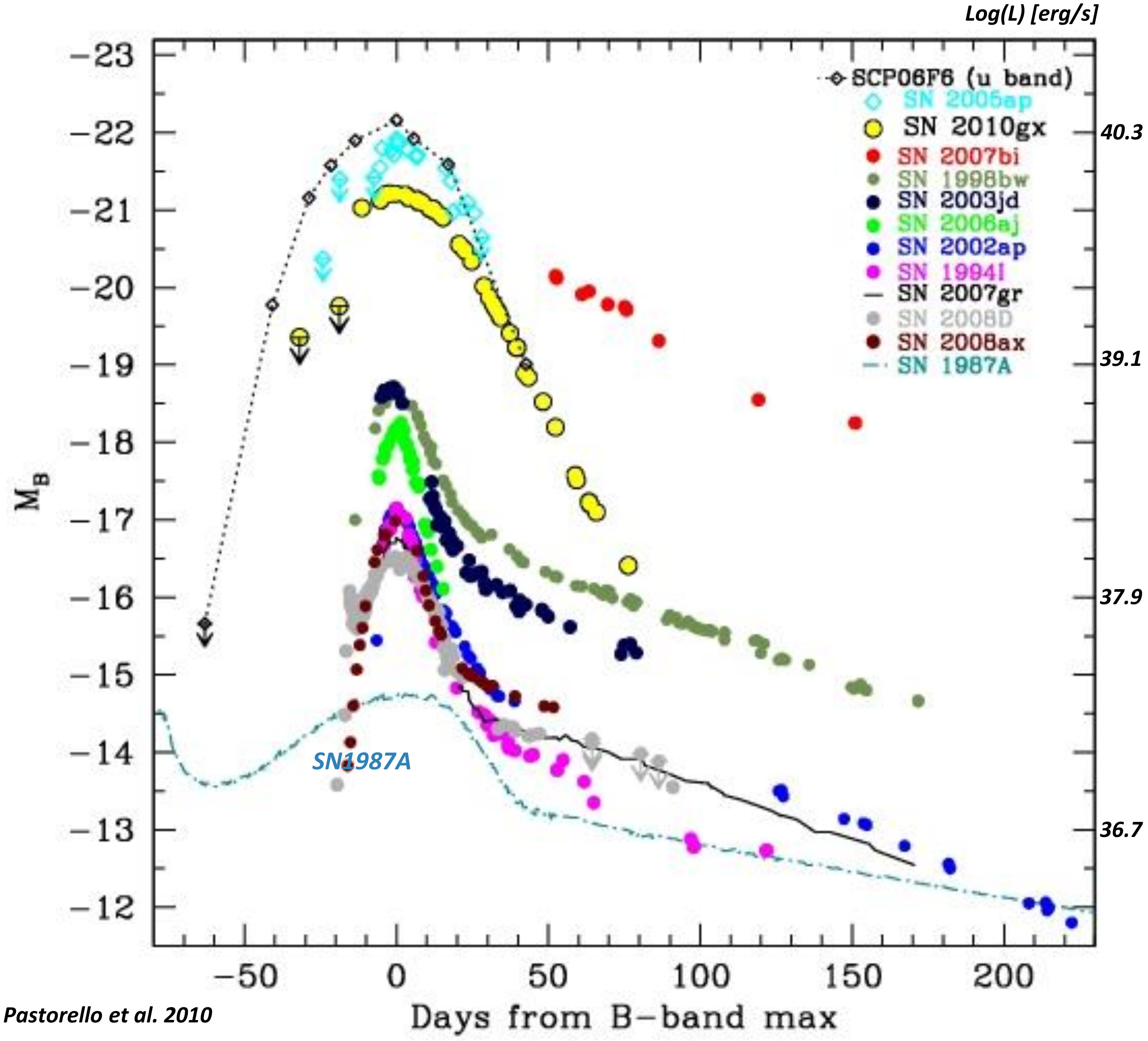
$$p + e^{-} \rightarrow n + \nu_e$$

This process is responsible for neutronization of massive stellar cores undergoing gravitational collapse (neutron star remnant formation)

neutron star



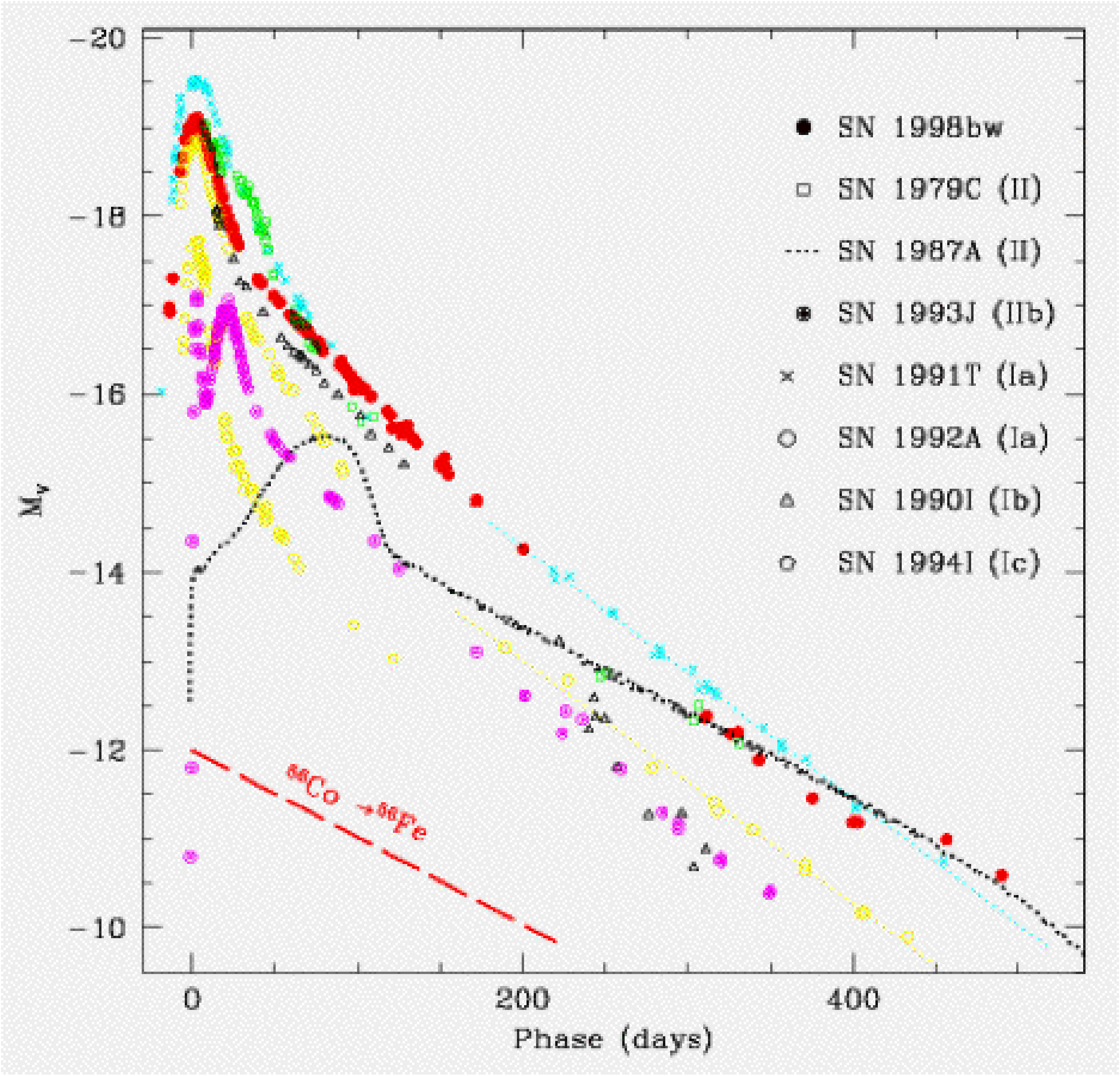
Light curves of core-collapse supernovae



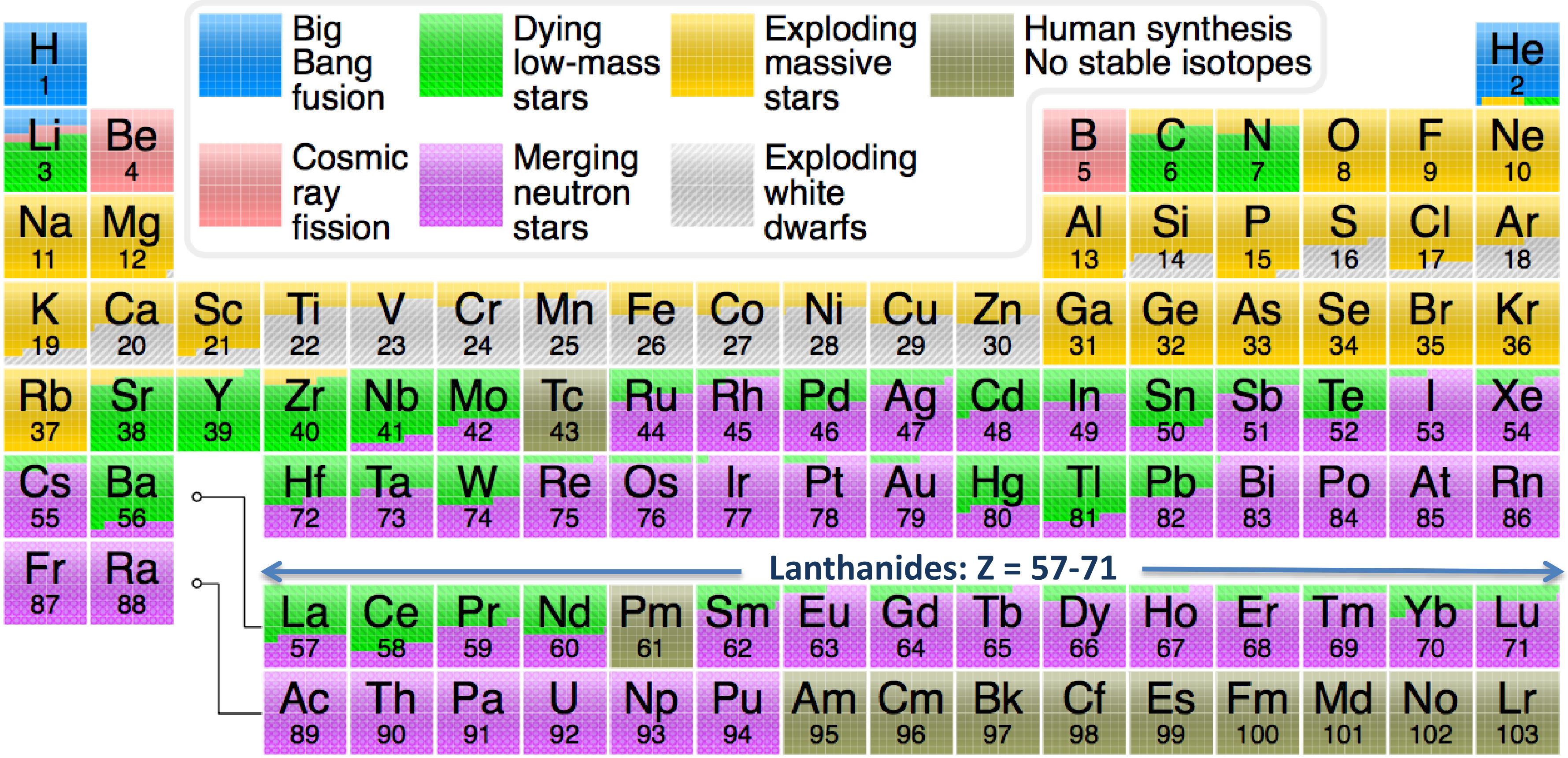
Adapted from Pastorello et al. 2010

SN Light Curves are diverse

Powered by decay of ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe



Periodic table of elements



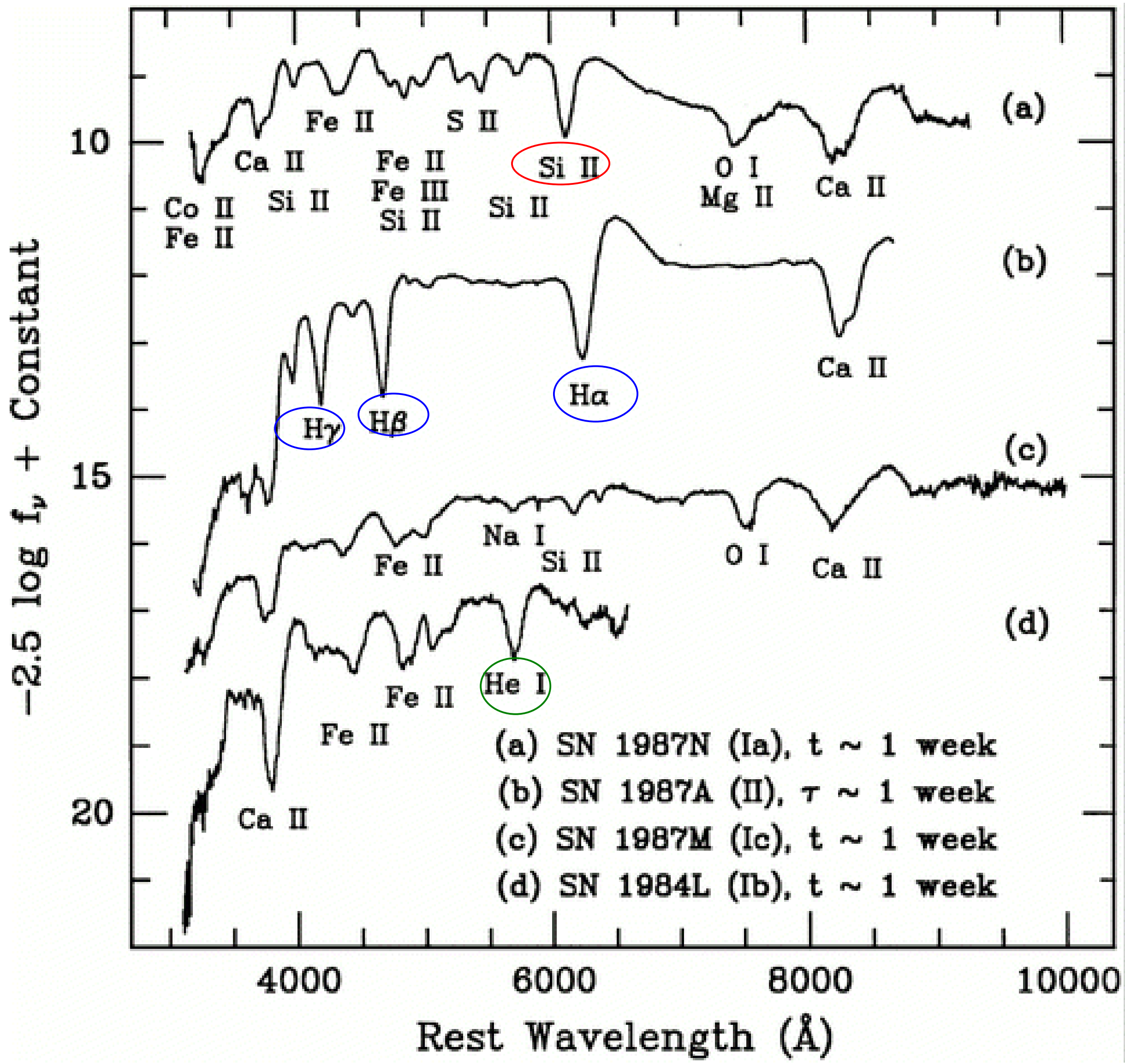
https://en.wikipedia.org/wiki/R-process

Electron capture (p + e- → n + nu_e) and beta+ decay (p → n + e+ + nu_e) Are also responsible for supernova light emission, dominated by the decay chain:

56Ni → 56Co → 56Fe

The emitted neutrino flux is normally way too weak to be detected

SN spectra near maximum light: diversity suggests different origin



SN Ia

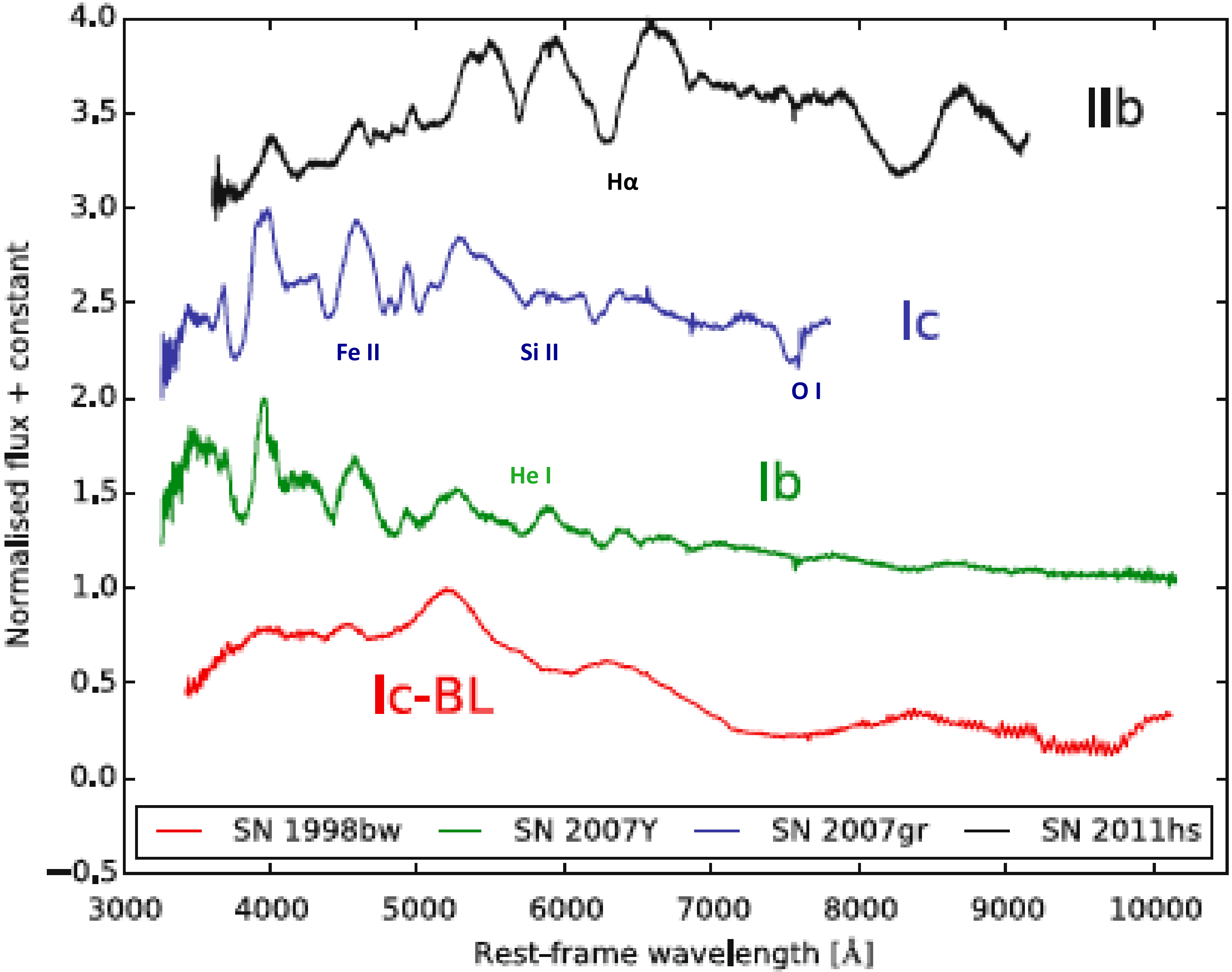
SN II

SN Ic

SN Ib

Filippenko 1997

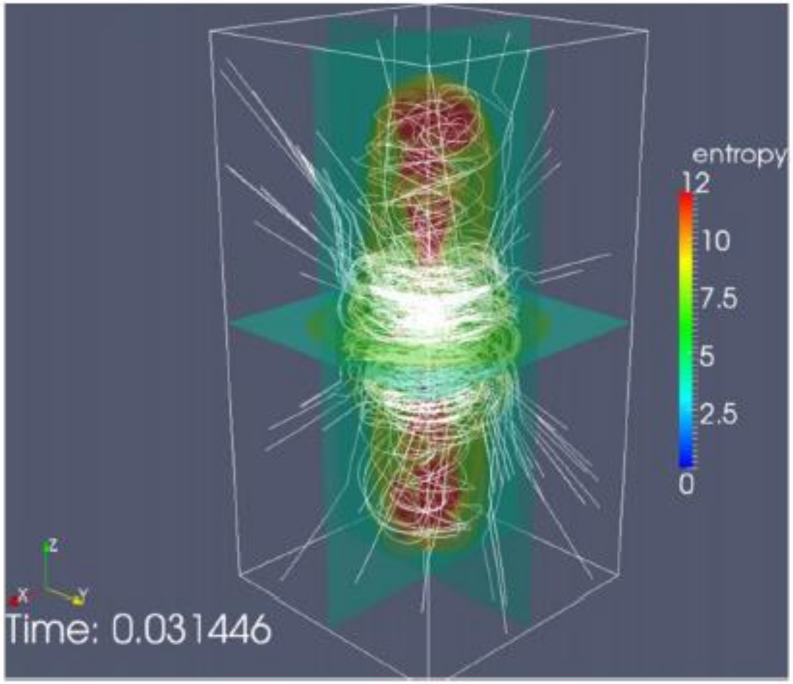
Typical spectra of Stripped-envelope core-collapse SNe



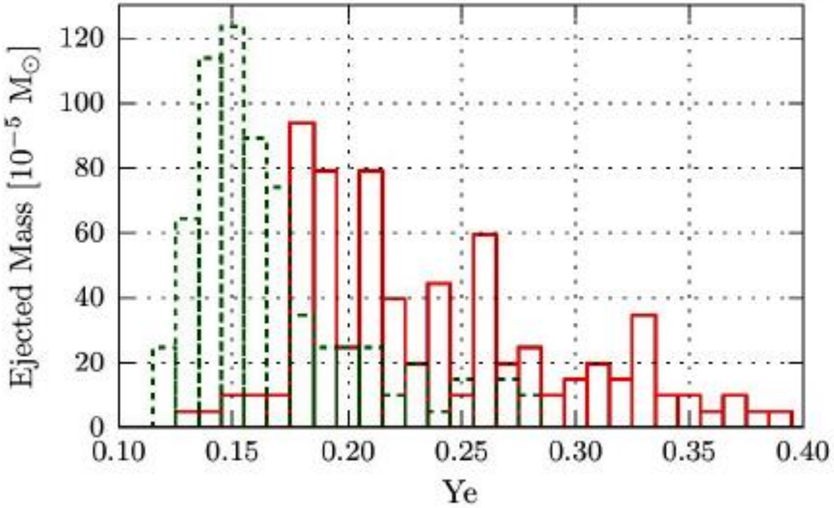
Pian & Mazzali 2017

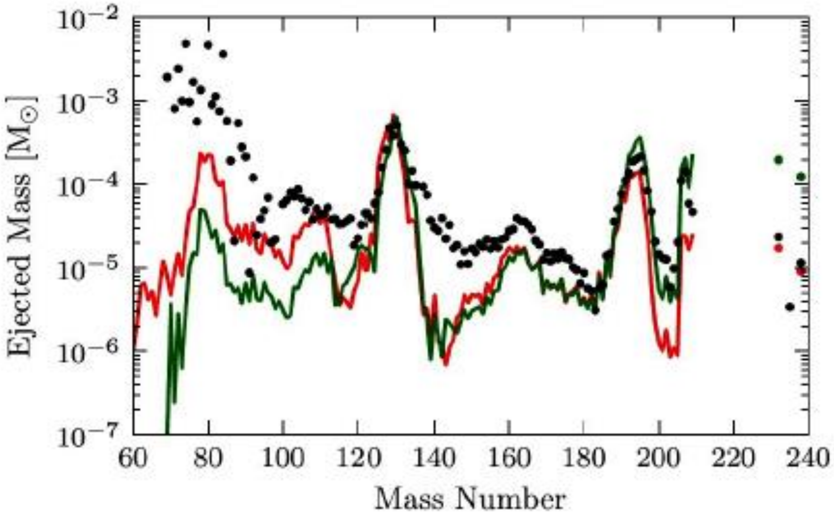
Jet-Supernova Models as r-process Sites?

- MHD-driven polar 'jets" could sweep out n-rich matter.
- Requires extremely fast matter ejection, extremely rapid rotation and extremely strong magnetic fields in pre-collapse stellar cores.
- Should be very rare event; maybe 1 of 1000 stellar core collapses?



Winteler et al., ApJL 750 (2012) L22



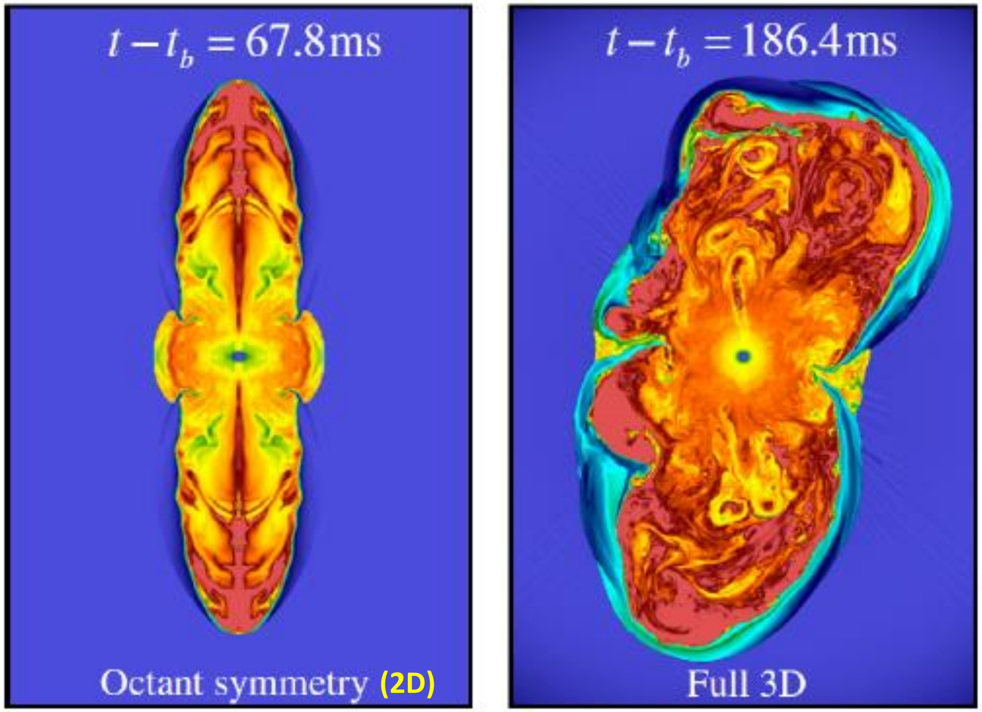


From Th. Janka, 2016

Jet-Supernova Models as r-process Sites?

BUT:

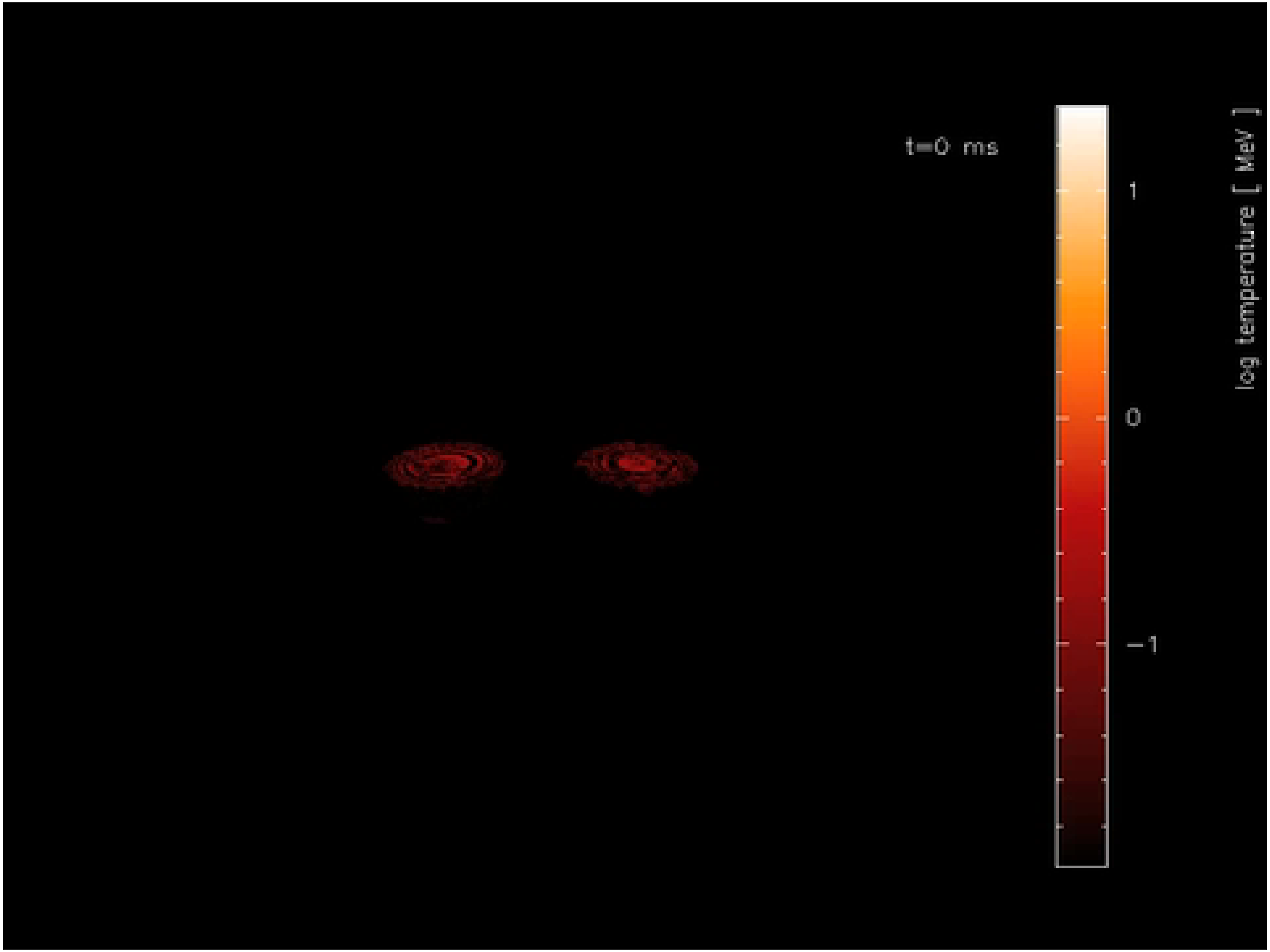
- MHD-driven polar "jets" in 3D develop kink instability.
- Assumed initial conditions not supported by stellar pre-collapse models.
- Dynamical scenario does not provide environment for robust r-process.



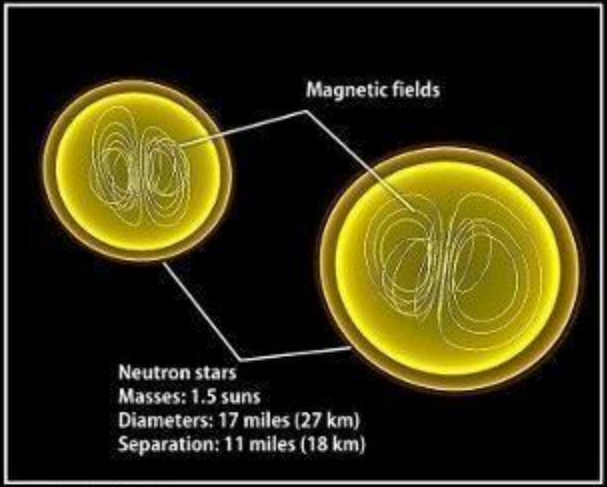
Mösta et al., ApJL 785 (2014) L29

From Th. Janka, 2016

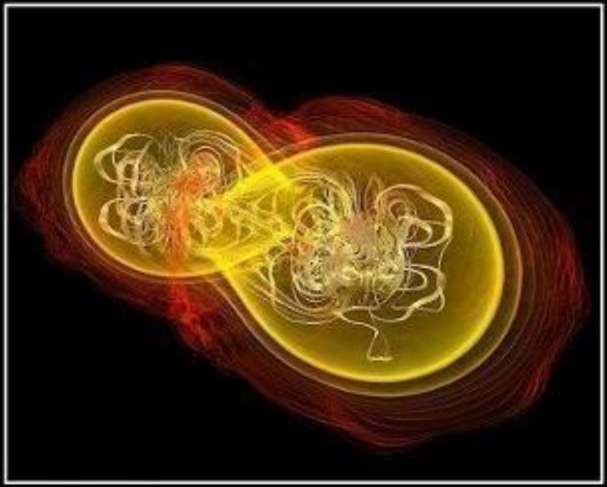
Simulation of the merger of a 1.3 and a 1.4 Msun neutron stars
(S. Rosswog, http://compact-merger.astro.su.se)



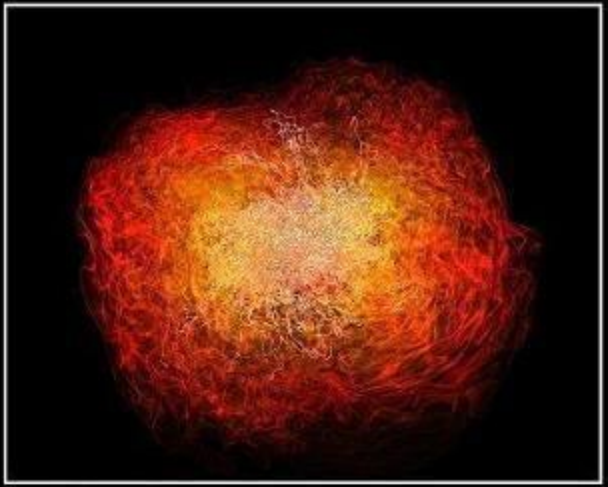
Crashing neutron stars can make gamma-ray burst jets



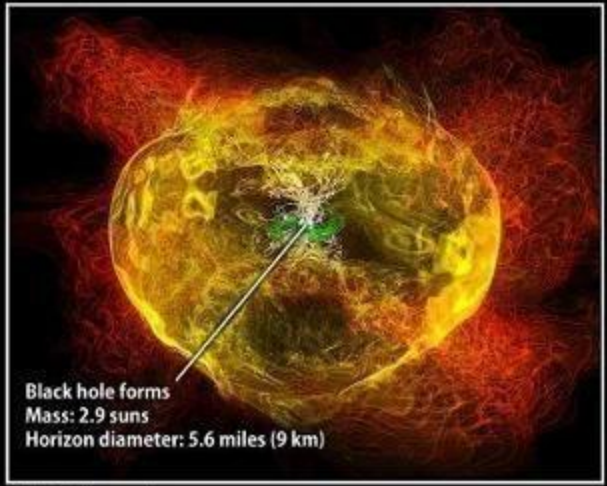
Simulation begins



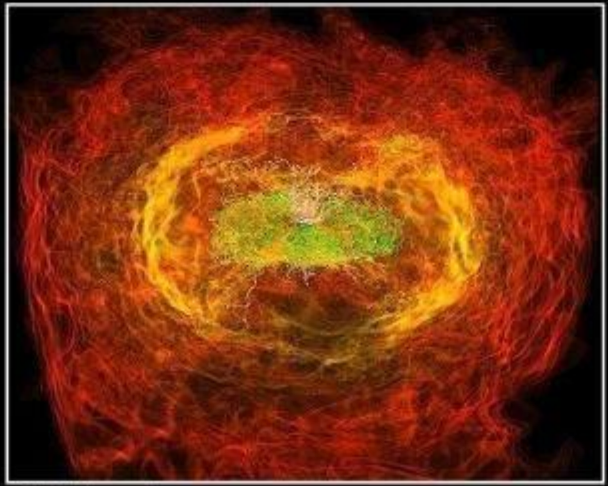
7.4 milliseconds



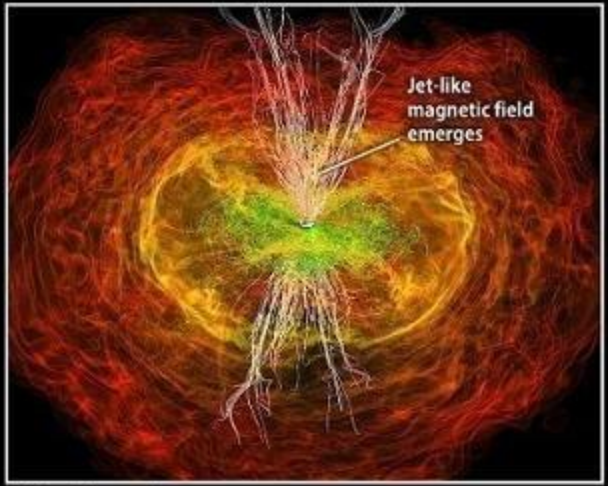
13.8 milliseconds



15.3 milliseconds



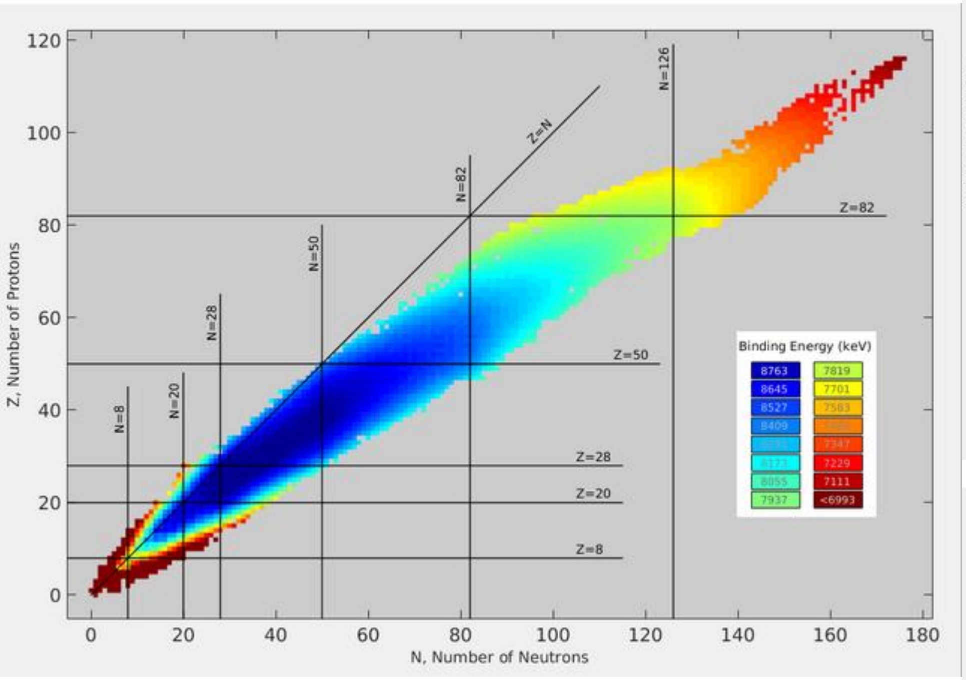
21.2 milliseconds

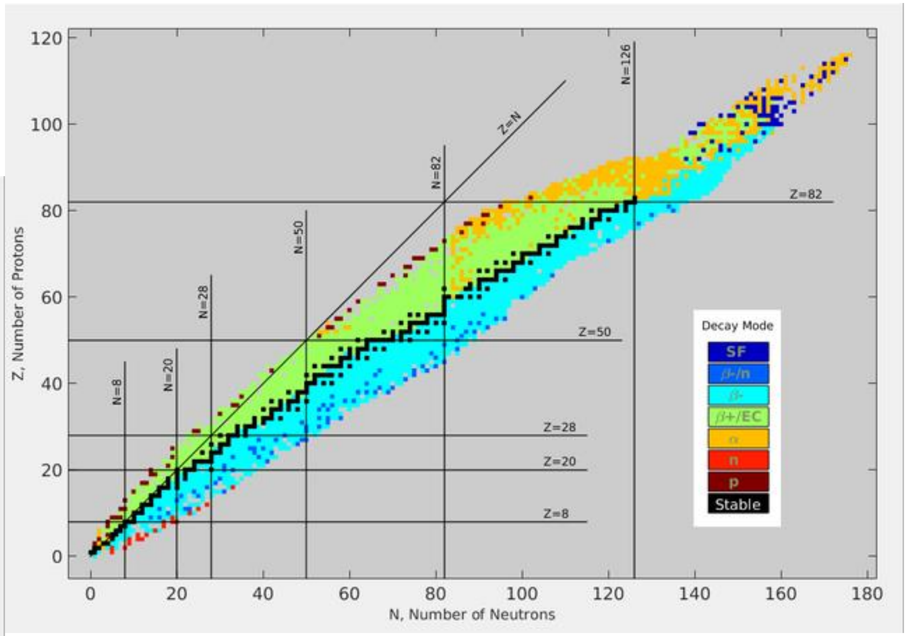


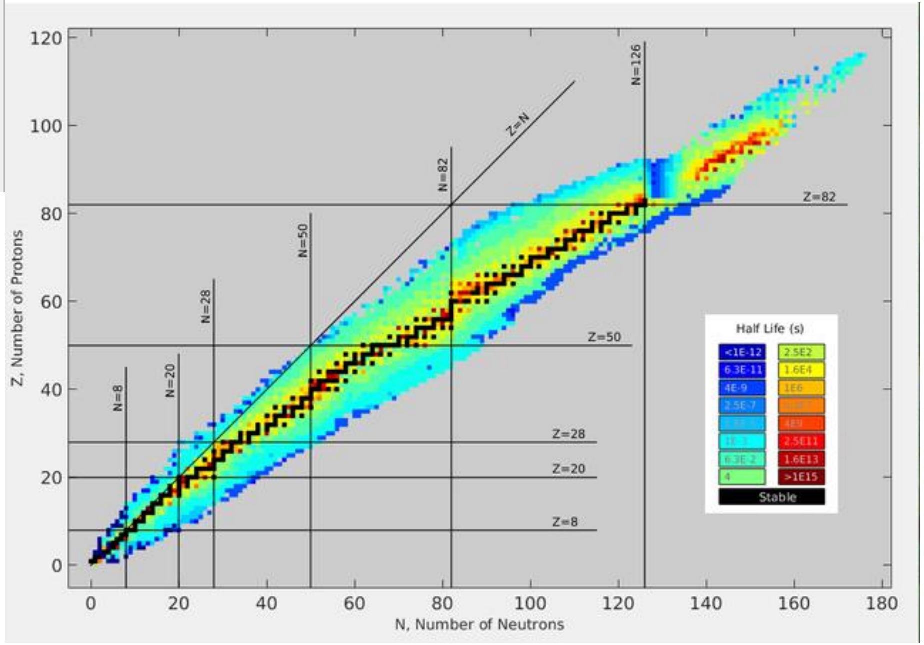
26.5 milliseconds

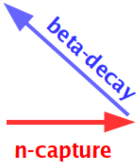
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

The valley of stability









beta-decay

n-capture

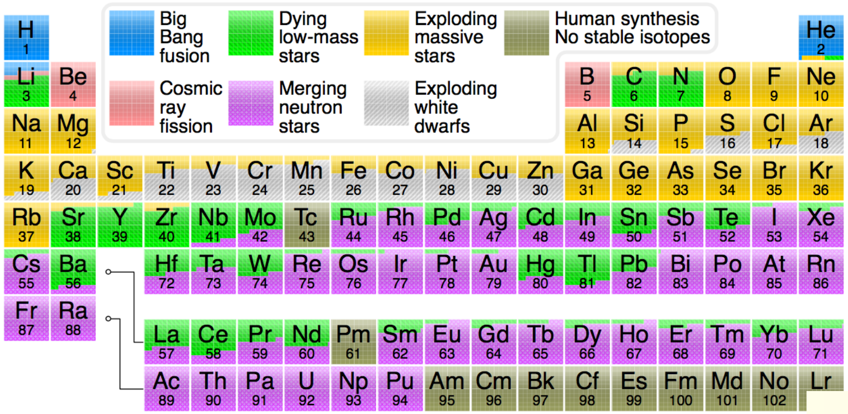
https://en.wikipedia.org/wiki/Valley_of_stability

See also:

https://www.youtube.com/watch?v=BaUjNiJYgO4
https://www.youtube.com/watch?v=UTOp_2ZVZmM&t=192s

Heavy elements: s- and r-process nucleosynthesis

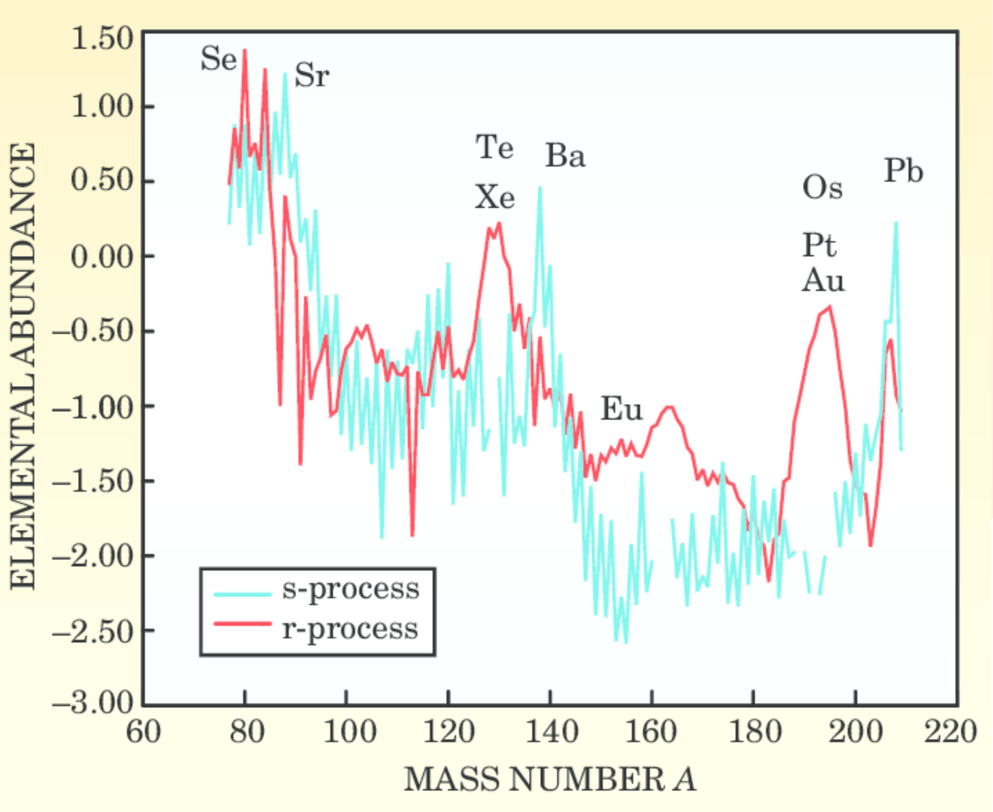
Periodic table



Solar system abundances of heavy elements produced by r-process and s-process neutron capture.

The s-process (~1000 years) takes place in red-giants cores (AGB phase)

The r-process (seconds or less) takes place in binary NS mergers



Short GRB130603B

(z = 0.356)

<u>Kilonova</u>:

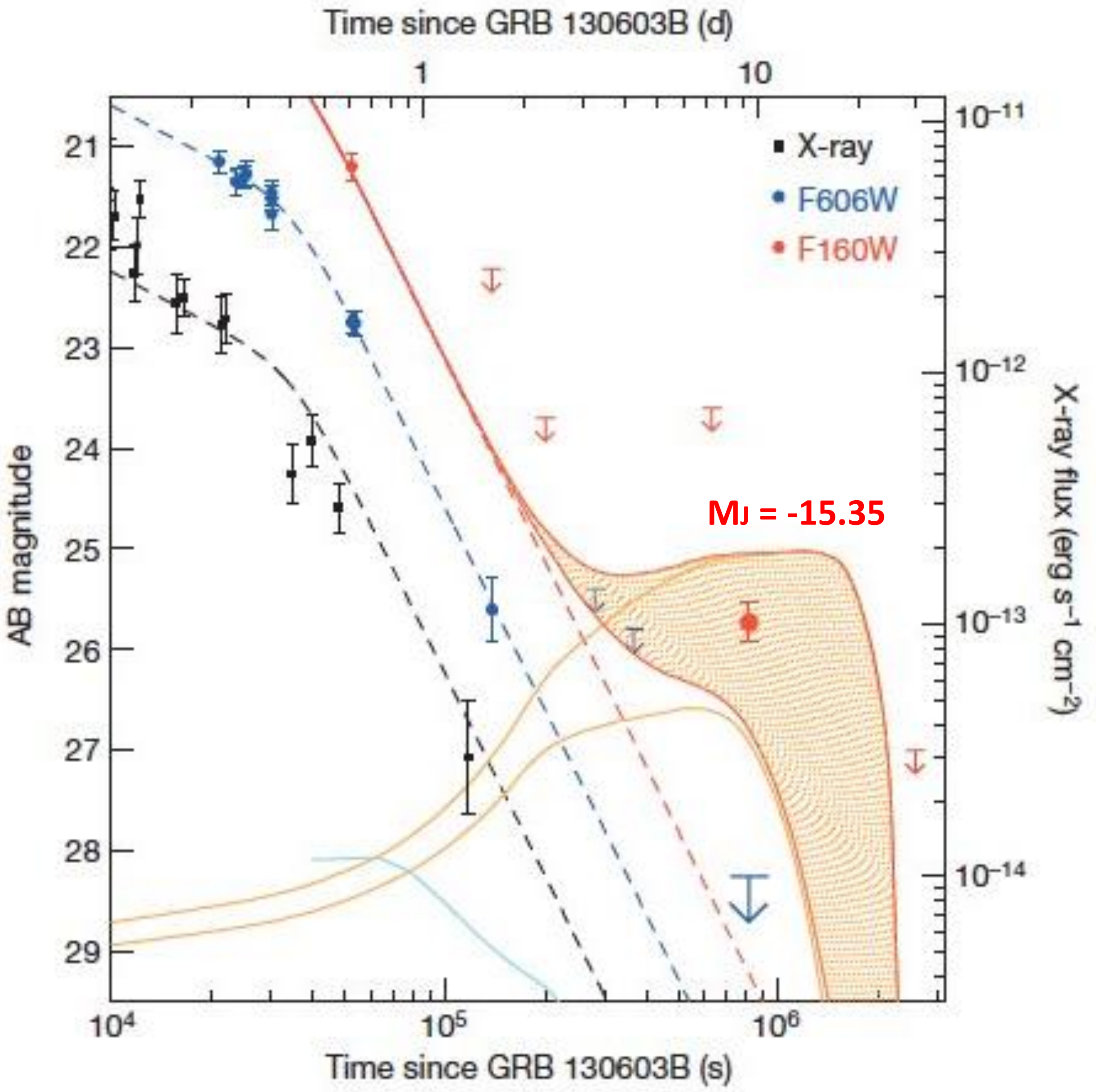
Ejection of r-process material from a NS merger (0.01-0.1 Mo) (Barnes & Kasen 2013)

$M_H \approx -15$

$M_R \approx -13$

Tanvir et al. 2013;

Berger et al. 2013



$M_J = -15.35$

Conclusions

Gravitational waves are a spacetime perturbation, described by a 4-dimensional tensor, produced by massive asymmetric sources.

First gravitational radiation detection (~100 Hz) in 2015 lagged theoretical prediction by one century, but results were spectacular: a binary system of black holes of 30 solar masses each merges and produces a nearly 60 solar mass black hole. The mass difference, 3 solar masses, is radiated away as GWs. However, no electromagnetic signal is detected, and none is expected (in principle).

The search for multiwavelength electromagnetic signal accompanying GWs from a binary neutron star merger has manifold implications: compact stellar object physics (NS EoS), binary merger dynamics, GRB physics, nucleosynthesis, MeV neutrino physics.

In particular, the optical/infrared counterpart of a binary NS merger is a radioactive source (kilonova), analogous to supernova.

Nucleosynthesis of binary NS merger points to dominance of r-process, as opposed to s-process: neutron fluxes are rapid and abundant.